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Vers du génie-civil situé : le cas de la construction en terre crue

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Antoine Pelé-Peltier

Toward situated civil engineering: the case of earth construction

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In front of the following examination committee:

Beckett Christopher / Associate Professor / Edinburg University	Reviewer
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Fabbri Antonin / Professor / ENTPE	Examiner
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Acknowledgement / Remerciements

I first would like to acknowledge the members of the jury and the reviewers for their valuable comments they have provided in the reports and during my PhD defence.

I had the chance to defend my PhD in front of my colleagues, friends and family, during which I ended with acknowledgement, in French. Here is the transcription:

Lors de ma soutenance, j'ai eu la chance de pouvoir lire aux personnes qui m'entourraient le texte suivant :

Puisque je crois que les mots s'ancrent dans les instants, j'aimerais profiter de ce moment pour inscrire quelques mots dans l'épaisseur de ce présent.

Je voudrais d'abord remercier profondément mes encadrant.e.s de thèse, Jean-Claude Morel et Rabia Charef. Merci pour la liberté et la bienveillance que vous m'avez offertes pendant ces quatres années mouvementées. Avec les quelques épreuves que nous avons traversées ensemble, j'aime à croire qu'un lien d'amitié s'est forgé.

Il me faut remercier beaucoup de personnes pour ma thèse, alors je vais devoir les rassembler par groupe pour ne pas que mes remerciements soient la section la plus longue de mon manuscrit.

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Il y a aussi mes ami·e·s qui s'amusent avec la terre. Mes cobureaux bien sûr, mais aussi le « DocTerre Crou »[1], parmi lesquels certain·ne·s ont largement contribué à mon bien-être pendant ce travail de thèse.

Il y a mes nouveaux ami·e·s et amours lyonnais aussi. Mon colocataire évidemment. Et puis, il y a des ami·e·s plus ancien·ne·s.

[1] Nom non-contractuel.

Celles et ceux rencontrés en école d'architecture, en école d'ingénieur, en prépa, et j'ai la chance de pouvoir remonter mes liens d'amitiés, sûrement les plus forts, jusqu'au lycée et même au collège.

Ça en fait du monde. Ça en fait des liens. Et aujourd'hui, mon plus grand accomplissement n'est sûrement pas d'avoir obtenu le grade de docteur[2], mais plutôt de vous avoir toutes et tous réuni·e·s ici, pour ainsi voir ces liens entrer en résonnance par les vibrations de nos cœurs.

Ces liens, ces fils, qui nous lient. Les voyez-vous ? Parfois fragiles et si beaux à la fois, parfois si solides qu'on sait parfaitement que jamais rien ne pourra les altérer, parfois rêches, jamais trop, et souvent doux. Quelques soit leur forme, ces fils me font, me portent, me grandissent, et tissent une magnifique tapisserie. Merci à vous d'être venu·e·s pour que je puisse aujourd'hui l'admirer.

Alors, certain·e·s s'en rendent compte, je l'espère. Ces fils, humblement, j'essaie de les entretenir du mieux que je peux avec l'héritage qui m'a été confié : L'amour. Celui-là qui prend racine dans les premiers liens qui m'ont soutenu et qui m'ont fait : Ma famille. Mon père, ma mère. Mes sœurs, ma force. Mes frères de cœur. Ces liens d'amour si fort, qui continuent à s'étendre vers mes six magnifiques neveux et nièces. En cet instant, je sais que vous ressentez beaucoup de fierté à mon égard. Mais, moi, c'est de vous dont je suis très fier.

Pour terminer, et rendre un hommage, j'emprunterai quelques mots à Alain Damasio dans *La horde du contre-vent* » :

> *« La solitude n'existe pas. Nul n'a jamais été seul pour naître. La solitude est cette ombre que projette la fatigue du lien chez qui ne parvient plus à avancer, peuplé de ceux qu'il a aimés, qu'importe ce qui lui a été rendu. »*

Puisse cette solitude ne jamais me gagner

Je le crois, car toujours, vous saurez me peupler

Merci.

A ma sœur, Céline

A mon père

[2] Mais j'en suis tout de même très heureux.

Abstract

In earth construction field, literature often start their introduction by pointing out *barriers to the use of earth in construction* that will be addressed then by their research question. However, it is frequent that these barriers are not scientifically justified (e.g. by citing a reference). This raise an issue of lack of rigour in introductions, but might also hide a lack of situating, from the perspective of situated knowledges theory. If the mentioned barriers do not represent a scientific reality, then they might express the values of the researchers without specifying them. In other words, they are situated knowledges that remains unaware of its situatedness. Therefore, the aim of this thesis is to reflect on the usefulness of situated knowledges theory in earth construction field, and more broadly in civil engineering.

To achieve this, a combination of research questions has been explored, starting with a typical civil engineering one: the development of a method of manufacturing rammed earth specimens, based on a similitude relation, allowing for obtaining representative results from the on-site. Then, in order to reflect on the situatedness of this first knowledge produced, the research question of "what are the barriers and drivers to the use of earth in construction?" was investigated. A literature review was first conducted, gathering all the articles addressing this research question. This review highlighted the diversity of cited barriers, which are of technical, economic, organizational, political, and socio-cultural nature. The analysis of the literature highlighted the usefulness of situated knowledges theory, when investigating such issue, by proposing a conceptual framework that will be useful for future research. To further the analysis, a case study of an office building with load-bearing rammed earth facades was conducted. The conceptual framework was adapted in this context, thus proposing a research method that could be used for future studies on the subject. This case study also allowed for discussing the barriers and drivers identified in the literature, highlighting that they do not always apply, and in any case, they are not insurmountable, under some conditions, including cooperation of different stakeholders, when analysing them at the scale of building design.

Lastly, the case study highlights the co-construction of a design method based on laboratory's testing, within which the method for manufacturing the developed specimens falls. Furthermore, the roles of different stakeholders, notably placing masons at the center, within this design method is described. This allows for situating the knowledge corresponding to the method for manufacturing specimens. Finally, a self-critique of the introduction of the corresponding published article is proposed. This provided elements for improvement in order to better situate our research in the field of earth construction. This development represents one of the main contributions to the science of this thesis.

Résumé

Introduction

Cette thèse s'inscrit dans un contrat de recherche avec l'ENTPE, Vaulx-en-Velin. Elle a pour principal objectif de montrer l'intérêt que peut avoir le paradigme des savoirs situés, proposé par Donna Haraway (1988), dans le domaine de la construction en terre crue. Ce nouveau paradigme, issue de l'épistémologie féministe, remet en cause le principe moderne de neutralité de la science. Au contraire, selon Donna Haraway, tout savoir, y compris scientifique, est situé, y compris la ou le chercheur.e (et ses valeurs) produisant ce savoir, dans des réalités socio-politiques. Le paradigme des savoirs situés aurait donc pour avantage d'assumer le caractère situé des savoirs scientifiques produits, et donc de gagner en objectivité et en rigueur scientifique. Alors que ces notions commencent à être courante dans les disciplines de sciences humaines et sociales, elles sont encore très marginales dans les disciplines de sciences naturels et physiques. On peut citer cependant Alessandra Quadrelli, chercheure CNRS en chimie, proposant depuis peu le concept de Chimie située. Cette thèse propose donc de porter une réflexion sur la neutralité, l'objectivité et les savoir situés dans le domaine du génie-civil et plus spécifiquement dans le domaine de la construction en terre crue.

La terre crue est un matériau ancestral de construction, oublié ces dernières décennies mais qui commence aujourd'hui à intéresser à nouveau, en particulier en France, pour ses vertus écologiques (matériau local, à faible énergie grise, confort thermique d'été, etc…). Ces dernières années, quelques bâtiments modernes en terre crue, plus spécifiquement en pisé (technique de mise en œuvre de la terre crue par compactage, typique de la région Auvergnes-Rhône-Alpes), ont été réalisés. C'est à partir de l'étude de cas d'un immeuble de bureau récent, en pisé porteur, de deux niveaux, que cette thèse propose d'investir cette notion des savoirs situés. En effet, dans le cadre à la fois de ce travail de thèse et de la construction de ce bâtiment, une recherche en génie-civil a été menée afin de développer une méthode de production d'éprouvettes permettant d'obtenir des résultats cohérents avec la réalité du chantier (chapitre 1). Cette étude, ayant fait l'objet d'une publication, a été réalisée avant d'avoir connaissance du principe des savoirs situés. Toutefois, l'article montre déjà une volonté de situer cette problématique dans le cas d'étude, notamment dans l'introduction de l'article. En effet, les introductions d'articles servent à situer les problématiques de recherche. Cependant, l'une des hypothèses de cette thèse est que celles-ci cachent parfois les valeurs des chercheur.e.s ayant écrit.e.s ces introductions. Dans une démarche de réflexivité, concordante au paradigme des savoirs situés, l'enjeu des chapitres suivants est donc de vérifier si cette première étude a été correctement situé et/ou d'améliorer la compréhension de cette situation.

La mise en avant d'hypothétique freins au développement de la construction en terre dans les introductions d'article est fréquente. Pourtant, ces freins ne sont que rarement justifié scientifiquement. Cela soulève ainsi une question de manque de rigueur qui pourrait cacher une absence de conscience du caractère situé de ces recherches. C'est donc sous l'angle de l'étude des freins et leviers à l'emploi de terre crue dans la construction que cette thèse propose de situer la problématique, et les savoirs associés, de génie-civil développée dans le chapitre 1. Une bibliographie des freins et leviers à l'emploi de terre crue dans la construction a donc d'abord été réalisée (chapitre 2), permettant de développer un cadre analytique soulignant l'importance de situer ce genre d'études. Ce cadre est ensuite réemployé dans l'étude de cas du bâtiment, dont la méthodologie, basé sur l'analyse de documents et d'interviews, est explicitée en chapitre 3. Le contexte de l'étude de cas est ensuite décrit en chapitre 4. Les problèmes rencontrés par les acteurs du projet sont ensuite décrits et analysés dans le chapitre 5. Finalement, le chapitre 6 permet de situer la recherche développée en chapitre 1, en particulier au sein de la méthode de conception employé dans ce cas d'étude.

Chapitre 1

Le chapitre 1 décrit une question typique de recherche en génie-civil. En effet, pour la conception de projet de construction en terre crue, il est parfois nécessaire d'évaluer la résistance à la compression des matériaux qui seront employés pour la structure, dans notre cas le pisé. Pour évaluer cette résistance en laboratoire, des éprouvettes de tailles réduites sont généralement testés. Cependant, aucune recherche n'avait encore étudié la représentativité des résultats obtenus à partir de ces éprouvettes en comparaison de la réalité du chantier.

Ainsi, à partir de l'analyse d'essais de compression simple, en laboratoire, sur 66 éprouvettes de différentes tailles et formes (des cylindres de hauteur 30 cm et de diamètre 15 cm, des prismes de hauteur 30 cm et de coté 15 cm et des prismes de hauteur 60 cm et de coté 30 cm, s'approchant des dimensions réelles du chantier), ce chapitre investigue la question de l'effet d'échelle entre petites et grandes éprouvettes. Ces éprouvettes ont en partie été fabriqué par des maçons, et en partie fabriqué en laboratoire, utilisant la même terre, parfois tamisée, auquel cas une relation de similitude sur les paramètres clés, que sont la densité sèche et la teneur en eau de fabrication, était utilisée.

L'influence de différents facteurs sur la résistance à la compression et la comparaison entre éprouvette est étudié, notamment l'influence de la teneur en eau, la densité sèche, la forme (cylindre ou prisme) et la granulométrie. A partir de cette analyse il est montré que la relation de similitude proposée auparavant pour la fabrication des échantillons de pisé permet d'obtenir une représentativité accrue du chantier. En particulier, elle met en évidence que le tamisage d'une terre en vue d'obtenir des résultats avec une faible variabilité de la résistance à la compression implique de prendre en compte des paramètres équivalents de densité sèche et de teneur en eau, à ajuster en fonction du chantier. Cette étude représente la première contribution scientifique de cette thèse et a fait l'objet d'une publication scientifique associée.

Dans cet article, nous avions déjà certaines intentions (mes co-auteurs et moi) de situer les connaissances produites pour cette étude. En effet, ces connaissances ont été introduites à partir de l'étude de cas. Cependant, à cette époque, nous n'étions pas conscients de la théorie des savoirs situées et ne prenions pas conscience du biais potentiel que peuvent présenter les introductions d'articles, en particulier en utilisant des hypothétiques "barrières" et "leviers" sans preuve scientifique. Par conséquent, afin de discuter de ce biais potentiel, il était utile d'établir une revue de littérature des articles abordant les barrières et les facteurs liés à l'utilisation de la terre dans la construction.

Chapitre 2

Ce chapitre propose une revue de la littérature abordant la question des freins et leviers à l'emploi de terre crue dans la construction. Pour ce faire, une méthodologie de revue systématique de la littérature a été adopté, basé sur 3 étapes de sélection : une première étape consistant à explorer la littérature sur le moteur de recherche Google Scholar, ceci permettant de s'approprier le sujet et d'établir les mots clés utilisés dans la seconde étape. Pour cette dernière, les mots clés préalablement sélectionné ont été implémenté dans le moteur de recherche Scopus. Des restrictions sur la recherche ont également été appliqué (Publications entre les années 2000 et 2023, restrictions aux domaines de recherche pertinents, …). Ainsi implémenté, les titres et résumés de chacun des articles résultants de cette recherche sur Scopus étaient consultés afin de procéder à la sélection. Finalement, une recherche dite « boule de neige » a été réalisé (i.e. consultation des références de chacun des articles sélectionnés à la seconde étape) sur Scholar a permis de vérifier l'exhaustivité du procédé de sélection des articles. De cette manière, 77 documents (incluant articles scientifiques, articles de colloque, chapitre de livre, thèses et mémoires de master) ont été sélectionné.

L'analyse de ces documents a permis de montrer d'une part qu'il existe une littérature relativement conséquente sur le sujet et qu'il était possible de classer les freins et leviers identifiés en cinq catégories : technique (Limitations liées aux propriétés du matériaux), économique (coûts, marchés, …), organisationnel (organisation de la conception, du chantier, …), politique (Normes, réglementations, labels …) et socio-culturel (perception du matériau, …). Ces catégories restent cependant interconnectées.

Une discussion approfondie de la littérature a permis d'identifier deux manières principales d'aborder ce sujet de recherche : soit en analysant les freins et leviers à l'adoption de la terre crue par certains acteurs ; soit en analysant de manière plus général les freins au *développement* de la construction en terre crue. Dans le second cas, nous avons identifié un manque de situation grâce à l'épistémologie féministe des savoirs situés. En effet, les études abordant la question par ce prisme ont tendance à manquer de contextualisation. Pourtant, l'analyse a montré que certains des freins dépendait du contexte socio-économique et géographique d'où était menée les études. Aussi, celles-ci tendent à invisibiliser qu'il existe différentes manières de considérer, d'une part ce qu'est aujourd'hui la construction en terre (suivant le contexte et les différentes visions des groupes d'acteurs) et d'autres part différentes perspectives de développement. En effet, en étudiant les freins et leviers au développement de la construction en terre crue, ces études ne font qu'analyser ce qui sépare l'état actuelle de la construction en terre crue de la vision dominante de la construction en général. Cette dernière peut être pourtant requestionner, par exemple par le prisme de l'économie circulaire.

Ce chapitre propose donc un nouveau cadre conceptuel, incluant le contexte et les acteurs, visibilisant la nécessité de définir correctement ce qui est entendu par freins et leviers dans les futures recherches sur le sujet. Ce cadre sera ainsi utilisé pour la suite de la thèse.

Enfin, comme il a été souligné précédemment, de nombreux articles scientifiques introduisent leurs problématiques de recherche par le biais d'hypothétiques freins à lever. Ce chapitre montre ainsi que la question des freins et leviers est bien plus complexe et que souvent ces articles manquent de bases scientifiques pour justifier ces barrières qu'ils adresseraient par le biais de leurs études. Ainsi, si les barrières avancées ne sont pas justifiées scientifiquement, et discutable suivant les contextes, cela veut donc dire qu'elles représentent un manque de situation (potentiellement associé aux valeurs portées consciemment ou non par les chercheur.e.s). Ce problème peut être analysé par le prisme des savoirs situés comme étant des représentations de la vision hégémonique (ou dominante) du *développement* de la construction en terre.

Afin de suivre le nouveau cadre conceptuel proposé et d'éviter le biais lié à un manque de situation des savoirs, une méthodologie d'analyse de cas d'étude a ainsi été proposé.

Chapitre 3

Pour la suite de cette thèse, une méthodologie d'analyse de cas d'étude d'un bâtiment moderne construit avec des façades en pisé porteuse sous la forme d'arche a été choisi. Cette méthode représente l'avantage de pouvoir proprement contextualiser et définir ce que veut dire freins et leviers dans ce contexte, ce qui sera fait dans le chapitre suivant. Bien que cette thèse n'ait pas la prétention de s'inscrire dans la discipline de la sociologie des sciences et des techniques, elle s'en inspire comme philosophie pour l'analyse du cas d'étude. En effet, ce dernier est considéré comme un objet socio-technique, ayant une histoire complexe, ici étudié entre la victoire du concours et la livraison du bâtiment, et faisant intervenir un grand nombre d'acteurs (maitrise d'ouvrage, architectes, ingénieur.e.s structure, thermicien.e.s, maçon.ne.s, etc…). Dans ce contexte, les catégories préalablement définies (technique, économique, politique, organisationnel, socio-culturel) au chapitre 2 seront utilisé comme prisme d'analyse.

Ce chapitre détail ainsi la méthodologie employées, consistant en une analyse de documents récupérés en rapport avec le projet (mails, plans, documents techniques et compte-rendu de réunion) ainsi que sur des interviews avec différents acteur.ice.s du projet (Maitrise d'ouvrage, architecte, ingénieur.e structure, ingénieur.e thermicien.ne, maçon.ne.s, contrôleur.e.s technique, chercheur.e). Les procédures d'analyses de ces données qualitatives sont décrites en détails et sont basés sur un principe de codage et thématisation de la donnée sur le logiciel Nvivo.

Enfin, une discussion est proposée sur la qualité de la recherche, notamment en termes de validité, de fiabilité et de transférabilité. De même les problèmes éthiques liés à la recherche menée dans cette thèse sont présentés relevant principalement du respect de l'anonymité des interviewé.e.s. Ce à quoi est ajouté une section sur l'éthique environnementale de cette recherche comme récemment recommandé par le comité d'éthique de la recherche du CNRS.

Chapitre 4

Ce chapitre a deux objectifs : le premier est de situer le cas d'étude dans son contexte et le second est de définir ce qu'on entend par freins et leviers dans le cadre de cette étude.

Ainsi, le contexte socio-économique et normatif français est d'abord discuté, et mis en perspective par rapport au système assurantiel français. Le rôle central du contrôleur technique dans ce système normatif-assurantiel est explicité. Ces informations seront utiles à la compréhension du chapitre suivant. Ensuite, d'autres éléments de contexte du bâtiment sont analysés, notamment le fait que le cas d'étude faisait partie d'un ilot regroupant plusieurs bâtiments, le tout dans un contexte d'aménagement urbain. Ce point est important car il permet de montrer que ce contexte interfère avec certains freins et leviers, en effet par exemple, le fait que le cas d'étude ne représentait qu'une petite partie (à la fois en terme financier et en termes de surface) représentait un réel avantage, notamment de flexibilité financière (et ce pour les différents acteurs) et de planification. Ensuite, les rôles des acteurs du projet sont précisés mettant en lumière la présence d'acteurs non-usuel comme les chercheur.e.s, les contrôleur.e.s techniques tierce partie ou encore les maçons. Le caractère peu commun du rôle des maçon.ne.s provenait de leur implication dès la phase de conception.

Enfin, la dernière partie définie l'élément de mur sur lequel une attention particulière dans cette thèse sera apporté. Il est montré que cet élément de mur, d'abord fictif (pendant la conception) puis réalisé, a en fait évolué. En effet, l'étude des plans et de la donnée (mails et entretiens) permet de montrer les différentes caractéristiques qui ont changées au cours du projet. Par exemple, bien que le pisé fût considéré dès la phase concours par la majorité des acteurs, son caractère porteur n'a été accepté par l'ensemble des acteurs que vers la fin de la réalisation. Ainsi, la conception de cet élément de mur s'est stabilisée au cours du projet suite à différents échanges entre les différents acteurs.

Ceci permet de définir ce qui sera considéré comme des freins et leviers dans le cadre du cas d'étude. D'abord, nous considérerons que l'objectif correspond au résultat du bâtiment, c'est-à-dire que nous observerons les freins et leviers vers du pisé porteur. Ainsi les freins à l'emploi de la terre crue dans le cas d'étude doivent être compris comme l'ensemble des contraintes et défis rencontré par les acteur.ice.s du projet pour parvenir à un consensus sur la solution technique des façades porteuses en pisé, prenant en compte le contexte urbain du bâtiment. Au contraire, les leviers seront tous les éléments ayant facilités l'obtention de ce consensus. De cette manière, les freins et leviers mesureront ce qui sépare l'élément de mur fictif (évoluant au cours de la conception) de l'élément de mur final, correspondant à la livraison du bâtiment. Ces freins et leviers pourront être d'ordre à la fois techniques, économiques, politiques, organisationnels et socioculturels et pourront dépendre du

contexte du bâtiment ainsi que du système technico-normatif. Ainsi défini, étudier les freins et leviers dans le cadre du cas d'étude revient à étudier les différents points de dissensus et les manières d'obtenir un consensus.

Chapitre 5

Ce chapitre se base sur la définition proposée en conclusion du chapitre précédent des freins et leviers à l'emploi de terre crue dans le cadre du cas d'étude. L'analyse de la donnée permet de mettre en évidence le premier obstacle rencontré : la remise en question constante du mur porteur en pisé. Celle-ci s'est exprimée d'abord par la remise en cause même de l'emploi du pisé, avec une contre-proposition de remplacé celui-ci par de la terre coulée lors de la phase d'Avant-Projet Définitif (APD), créant ainsi une controverse. Celle-ci est survenue notamment en raison d'un conflit opposant deux équipes au sein de la maitrise d'œuvre. Ceci souligne l'importance de convaincre toutes les parties prenantes du choix de la technique de mise en œuvre au plus tôt dans la conception du projet. Cependant, ce conflit a eu l'avantage de soulever différents potentiels problèmes liés au pisé, qui ont ensuite dû être traité par l'équipe de maitrise d'œuvre. On peut citer notamment la gestion de l'érosion ainsi que le manque de concurrence entre entreprises lors des réponses aux appels d'offres, en raison d'un manque d'entreprise qualifiée pour y répondre. La maitrise d'ouvrage a exigé que les deux techniques soient étudiées durant toute la phase APD, demandant notamment d'expliciter les coûts de chacune et le potentiel besoin d'une procédure d'ATEx. Ceci met en évidence certaines préoccupations de la maitrise d'ouvrage qui peuvent guider leur choix. La proposition terre coulée a finalement été rejetée à la fin de la phase APD. La capacité portante du pisé a cependant continué à être remise en question, notamment par le contrôleur technique, jusqu'à la livraison du bâtiment. En effet, en raison d'un manque de référentiels (normes, règles professionnels, etc…), d'un manque de preuves scientifiques et d'un manque de confiance soit dans le pisé porteur, soit dans la conception proposée par l'équipe de maitrise d'œuvre, ou les deux, les contrôleurs techniques ont fait appel à une procédure d'ATEx. Cette procédure, que souhaitaient éviter la maitrise d'ouvrage et la maitrise d'œuvre, représentait un risque en cas de rejet, car cela aurait pu être synonyme de coûts assurantiels supplémentaires. Malgré un travail conjoint entre les ingénieurs structures, les chercheurs et l'entreprise de pisé (qui était porteuse de la démarche), le rapport d'ATEx a finalement été rejetée par la commission, pour deux principales raisons : un coefficient de sécurité considéré trop faible et un manque de justification de l'absence de fluage du pisé. Ceux-ci seront discuté dans le chapitre suivant. Ainsi, le projet aurait pu être bloqué, mais les contrôleurs techniques ont finalement accepté de passer par un avis technique simple. Lors du refus d'ATEx, le chantier et la production des blocs de pisé étaient déjà commencé, il était donc difficile de revenir en arrière pour l'ensemble des acteurs du projet. Ceci

met en évidence le rôle crucial joué par les contrôleurs dans l'étude de cas, à la fois obstacle (par le biais de la demande d'ATEx), à la fois levier. Ce paragraphe illustre ainsi les obstacles rencontrés par les équipes de conception lorsqu'elles conçoivent des bâtiments à l'aide de matériaux non normalisés (aux référentiels non approuvés par la C2P), en particulier lorsque le matériau est porteur.

Après le refus d'ATEx, une négociation s'est enclenchée entre les contrôleurs techniques et l'équipe de conception, les premiers continuant à remettre en cause la capacité portante du pisé dans le cadre du projet et proposant l'ajout de poteaux bois en façades. Ainsi, le caractère porteur de la technique considérée est important à prendre en compte dans l'étude des freins et leviers. Bien que la capacité portante du pisé ait été un point majeur de dissensus entre les acteurs du projet, d'autres éléments ont également fait l'objet de discussions. En particulier, ce chapitre décrit les négociations et décisions autour de la gestion de l'érosion du pisé et de l'emploi potentiel d'une isolation, les deux étants liés à la sensibilité à l'eau du matériau. L'étude de cas souligne que la justification de la gestion de l'érosion n'a pas représenté de difficultés particulières. En effet, grâce aux connaissance pratiques des maçons et aux échanges de connaissances entre les parties prenantes, différentes solutions ont rapidement été trouvés pendant la phase APD. Pourtant, la sensibilité à l'eau lié à la faible durabilité du matériau est souvent avancée comme un obstacle à l'utilisation de la terre crue dans la littérature. Notamment dans des articles proposant une recherche sur la réduction de la sensibilité à l'eau par l'emploi d'adjuvants. Ceci illustre ainsi le biais déjà identifié dans le chapitre 2 qui consiste à justifier en introduction d'article une recherche spécifique par le biais d'hypothétique « freins » à la construction en terre.

Tous ces choix techniques sont en fait le résultat d'un processus négocié et collaboratif (plus ou moins facile et plus ou moins long) entre différents acteurs, soulignant ainsi l'importance du travail d'équipe. Ce dernier, basé sur la confiance entre certains acteurs du projet et leurs motivations, a en effet été relevé comme un facteur clé de la réussite du projet. Ces motivations se rejoignaient autour de l'envie de faire un bâtiment « démonstrateur », bien que le sens de celui-ci ne fût pas le même pour tous les acteurs. D'autres motivations comme un enjeu de réputation, ainsi que des investissements de long terme et le retour d'expérience que représentait le projet ont été identifiées. Ces dernières peuvent être vu comme des leviers pour motiver les différents acteurs de futurs projets en pisé.

Ce processus négocié, en particulier entre le bureau de contrôle et le bureau d'étude structure, a abouti à la mise en œuvre d'une méthode de justification spécifique, développée par l'équipe de conception étendue (c'est-à-dire incluant les chercheurs et les maçons). Cette méthode fera l'objet du dernier chapitre et permettra de situer le savoir produit dans le premier chapitre de cette thèse.

Chapitre 6

Ce chapitre décrit d'abord différentes approches de méthodes de conception (performancielle et prescriptives notamment) sur lesquelles peuvent se baser la création de futures normes. Ces méthodes ont des implications socio-politiques. En effet, en France, des groupes de professionnels utilisent l'approche dite « performancielle » (en opposition donc à l'approche prescriptives) pour sécuriser le rôle actuel des artisans dans le processus de construction (Similaire à celui jouer par les maçon.ne.s dans l'étude de cas), ainsi que la possibilité d'utiliser la terre locale dans les projets de construction. Ces différentes positions expliquent pourquoi la question de la création de nouvelles normes, pour surmonter l'obstacle que représentent leur absence, n'est pas une tâche aisée et ne fait pas consensus au sein de la profession. Ces implications socio-politiques doivent donc être prises en compte. Mettre en lumière celles-ci a permis de situer l'approche de conception par l'expérimentation de l'étude de cas, que l'on peut définir comme une approche performancielle, et qui a en effet placée les artisans dans un rôle centrale.

Cette approche, considérée comme un levier dans l'étude de cas, car elle a contribué à surmonter la plupart des obstacles liés à la capacité portante du pisé, repose sur cinq étapes clés : approvisionnement en matériaux terre, prototypage, caractérisations, préfabrication et contrôle qualité. Ces étapes sont détaillées dans ce chapitre et leur interconnexion est mise en avant. Une mission spécifique a d'abord été confiée aux maçons par la maitrise d'ouvrage pour procéder à la recherche et approvisionnement de la terre. Cette dernière était contrainte à la fois par le label BREAAM, qui imposait une distance de 30km par rapport au chantier, et par le contexte urbain avec la présence de terre polluée sur site, ne pouvant donc pas être utilisées. Une fois la terre sélectionnée, une caractérisation de la résistance à la compression d'échantillons de pisé fabriqués par les maçons a été réalisée en laboratoire afin d'établir la valeur de conception. En parallèle, des prototypes ont été fabriqués par les maçons afin que l'équipe de conception (notamment les architectes) ainsi que la maitrise d'ouvrage valide le choix de la terre. A partir de ces prototypes, des paramètres ont été mesurés pour poursuivre les caractérisations, notamment de l'évolution de la résistance à la compression en fonction de la teneur en eau et du temps de séchage du pisé. Celles-ci ont été utiles pour le contrôle qualité. Ce dernier était principalement souhaité par les contrôleurs techniques, même s'il permettait également de rassurer les concepteurs et les maçons. Il comprenait le contrôle de la densité sèche des blocs et du processus de séchage, afin d'informer les ingénieurs structures, qui autorisaient ensuite la mise en œuvre des blocs en fonction de la montée en résistance de ceux-ci. D'autres contrôles qualités ont été demandé par les contrôleurs techniques pour suivre le bâtiment

après sa livraison : le suivi du fluage, le contrôle visuel par les maçons, ainsi que le suivi hygrothermique intérieur.

Enfin, la méthode développée au chapitre 1 a été située dans ces étapes clés en tant que potentiel d'optimisation du processus de caractérisation. Cela a permis de situer ces connaissances parmi les implications socio-politiques potentielles liées à l'approche de conception et plus largement à la création de futures normes. En effet, si cette méthode était destinée à être développée pour la création de normes, puisqu'elle est basée sur des paramètres de chantier, lié à la mise en œuvre des maçons, elle pourrait sécuriser leur rôle dans le processus de conception. Enfin, ce besoin de situer les recherches dans le domaine de la construction en terre est illustrée par une autocritique de l'introduction d'un article publié à partir des connaissances du chapitre 1. Cela s'inscrit dans une approche réflexive en accord avec la théorie des connaissances situées, et pourrait ainsi contribuer à tendre vers une recherche située.

Conclusion

L'objectif de cette étude était d'explorer comment la théorie des savoirs situés pourrait être utile dans la recherche en génie civil. Cette thèse a donc débuté par une question de recherche en génie civil et la présentation des connaissance produites associés : le développement d'une méthode de fabrication d'éprouvettes de pisé, basé sur une relation de similitude, permettant d'obtenir des résultats représentatifs du terrain. Ensuite, l'objectif était de situer ce savoir (c'est-à-dire de rendre visible leur interaction complexe avec des réalités socio-politiques). Pour ce faire, il a été choisi d'étudier les freins et leviers à l'utilisation de la terre dans la construction. En effet, il a été remarqué que les introductions d'articles scientifiques (Là où les savoirs sont généralement situés par les auteur.ice.s) dans le domaine de la construction en terre font souvent référence à des freins supposés à son développement pour justifier leurs recherches. Supposés, car celles-ci ne se basent généralement sur aucune preuve scientifique. L'hypothèse de cette thèse était donc que, si les freins mentionnés ne représentent pas de réalité scientifique, alors ils expriment peut-être les valeurs des chercheur.e.s, sans les spécifier. Autrement dit, ce sont des savoirs non-situés, ou des savoirs situés qui s'ignorent. Pour discuter de ce problème, une revue de la littérature a d'abord été menée rassemblant tous les articles abordant la question des freins et leviers. Celle-ci a permis de mettre en évidence la diversité des freins cités, qui sont d'ordre technique, économique, organisationnel, politique et socio-culturel. L'analyse de cette littérature a également mis en évidence un bais, notamment due à un manque de conceptualisation de certaines de ces études. Un cadre conceptuel a donc été proposé pour la suite de la thèse. Pour poursuivre l'analyse, une étude de cas d'un immeuble de bureau dont les façades sont en pisé porteur a été réalisé. Le cadre conceptuel a été adapté dans ce contexte proposant ainsi une méthode de recherche pouvant être utilisée pour de futures recherches sur le sujet. Cette étude de cas a également permis de discuter les freins et leviers repérées dans la littérature, mettant en évidence que ces derniers ne s'appliquent pas toujours, et en tous les cas ne sont pas insurmontables, lorsque l'on reporte l'analyse à l'échelle de la conception d'un bâtiment. Enfin, l'étude de cas a mis en évidence la co-construction d'une méthode de conception basée sur l'expérimentation, dans laquelle s'inscrit la méthode de fabrication d'éprouvettes développée au début de la thèse. De plus les rôles des différents acteurs, mettant notamment au centre les maçons, au sein de cette méthode de conception ont été décrit. Ceci a permis de situer le *savoir* correspondant à la méthode de fabrication d'éprouvettes dans un complexe socio-technique. Enfin, une auto-critique de l'introduction de l'article publié correspondant a été proposée. Celle-ci a permis de proposer des éléments d'amélioration pour mieux *situer* nos recherches dans le domaine de la construction en terre. Ce développement représente l'une des principales contributions à la science de cette thèse.

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List of Abbreviations

AEC Architectural, Engineering and Construction

AQC Agence Qualité Construction (recognised body that can approve standards)

ATEx Appréciation Technique d'Expérimentation

BREEAM Building Research Establishment Environmental Assessment Method

BIM Building Information Modelling

CCTC Confederation of raw earth construction

CE circular economy

CNRS Centre National de la Recherche Scientifique

CS Compressive Strength

CSTB Centre Scientifique et Technique du Bâtiment

C2P Comission Prévention Produit (Specific commission of the AQC dedicated to the approval of standards)

EN Euronorm

EST Ecological and solidarity transition

GDBP French guide of earth construction good practices (Guide Des Bonnes Pratiques)

HQE Haute Qualité Environnementale

ICOMOS International Council on Monuments and Sites

IPCC Intergovernmental Panel on Climate Change

PE Poured Earth

PRISMA-P Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols

RE Rammed Earth

RIBA Royal Institute of British Architects

RQ Research Question

RILEM International Union of Laboratories and Experts in Construction Materials, Systems and Structures; acronym RILEM comes from the name in French

SE Structural Engineers

SK Situated Knowledges

TCE Testing and Characterisation of Earth-based building materials and elements

ZAC Zone Aménagement Concertée

General introduction

"Faced with the huge upheavals that lie ahead, our era needs a body of knowledge - scientific and social - of greater breadth and depth, in order to solve the problems we face. […] ***We can no longer afford to remain captive to the tendency of classical science to dissect phenomena and examine their fragments. We have to combine them, link them together, observe them in their totality as well as in their specificity.****" (Bookchin, 2012, p. 21)*[3]

This chapter will describe the aim and objective of the PhD thesis. Some concepts that are useful for the understanding of the manuscript are introduced including situated knowledges theory and earth construction field.

[3] Translated from French to English by the author. Original version: *"Face aux gigantesques bouleversements qui nous attendent, notre époque a besoin d'un corpus de savoir – scientifique et social – d'une envergure et d'une profondeur plus grandes, afin de résoudre les problèmes qui se posent à nous. […]* ***Nous ne pouvons plus nous permettre de rester captifs de la tendance de la science classique à disséquer les phénomènes pour en examiner les fragments. Nous devons les associer, les relier, les observer dans leur totalité autant que dans leur spécificité.*** »

1. Introduction

In September 2018, after finishing a double master's degree in architecture and civil engineering, I was about to start a year of internship. In architecture school, I already have discovered earth construction for which I got directly interested in. Particularly in the environmental and social values and reflection that this field can carry. At that time, I started to feel the potential of earth construction field to raise questions about societies. That's why I have decided to start research work through my first 6-month internship. However, this research work was quite specific as it was directly linked to a remarkable modern earth building in construction (Figure 0.1), and therefore closely linked to professional realities. I have then followed this project from different environments (University for the first internship, and structural design office for the second), and finally chosen it as the case study for this thesis. Those two internships allowed me to start questioning the place of research in society, in particular the tension between the short-term needs raised during the building project and the long-term knowledge-production process of research. In parallel, although I was already aware of the environmental issues, my readings helped me to realize the urgency of the situation, which raised to me even more questions about scientific research, particularly questioning the usefulness considering the feeling of urgency.

In this context, in September 2019, I started my PhD thesis in the civil engineering discipline, carrying quite a lot of questions. The first event I attended raised even more questions: A meeting of the RILEM[4] committee dedicated to earth construction. After spending a year following a specific construction project, where I realized that many problems that designers faced when using earth material were not technical, I felt disappointed. Indeed, on the one hand, the meeting never referred to real constructions and on the other hand all the presentations were dedicated to technical issues[5]. Of course, I do not deny the usefulness of the research carried by the committee. However, due to my multidisciplinary background and my questioning, I needed to see other forms of research. That is probably how I started to discuss with Jean Goizauskas, a PhD student in science studies, with who we gathered a group of multidisciplinary PhD students of about 10 members. Through different discussions, I also realized that technical problems cannot be seen as only "technical" and had socio-political implications. This means that creating knowledge can both have positive and negative implications in socio-political realities. This raised to me a feeling of responsibility, that I first struggled to address. Hence, while I started this PhD thesis with proper civil engineering issues (basically,

[4] International Union of Laboratories and Experts in Construction Materials, Systems and Structures, https://www.rilem.net/
[5] This is, however, what it is expected from the RILEM committee. Indeed, this research committee is dedicated to the creation of standardized testing procedures. But at that time, I was not aware of the purpose of such research groups.

breaking test specimens, measuring, and analysing quantitative results), from which I produced knowledge, I felt the need to *situate* this knowledge in socio-political realities.

Additionally, with the climatic urgency awareness, I felt a need for commitment. That is why, along with the will to produce a different form of research I was supposed to, I started to get involved in different events or with different organizations. This raises again new issues, particularly the one of neutrality and objectivity of science and research, but also brought some answers: particularly, regarding the concept of situated knowledges[6]. This concept will be more thoroughly described in this chapter, but in a few words, it offers an opportunity for more rigorous science production taking into consideration the interaction with society. This concept helped me to gather the different works achieved during my PhD: (1) a mechanical study; (2) a literature review on barriers and drivers to the use of earth in construction; and (3) the analysis of a building's case study. It actually helped me to define the aim of this PhD thesis: **trying to demonstrate the usefulness of situated knowledges concepts for further studies in earth construction** in civil engineering and more broadly non-human science research. Indeed, situated knowledges requestion neutrality in science and redefine objectivity. This seems particularly crucial when the place of research in society should be questionned considering the environmental upheaval. Therefore, this chapter will introduce the aim of the thesis first by reminding some insights on the environmental and climatic urgency, highlighting the different research groups that struggle against climate change and in parallel requestioning the place of research in society. This will be also a way to position myself among those groups, through a declaration of values. The concept of situated knowledges will then be described as an opportunity for better science in this context. Then, earth construction will be introduced to understand how situated knowledges theory might be useful in this domain by introducing the research aim. And finally the thesis structure will be outlined.

[6] Adding a « s » to knowledge is voluntary and will be explained later.

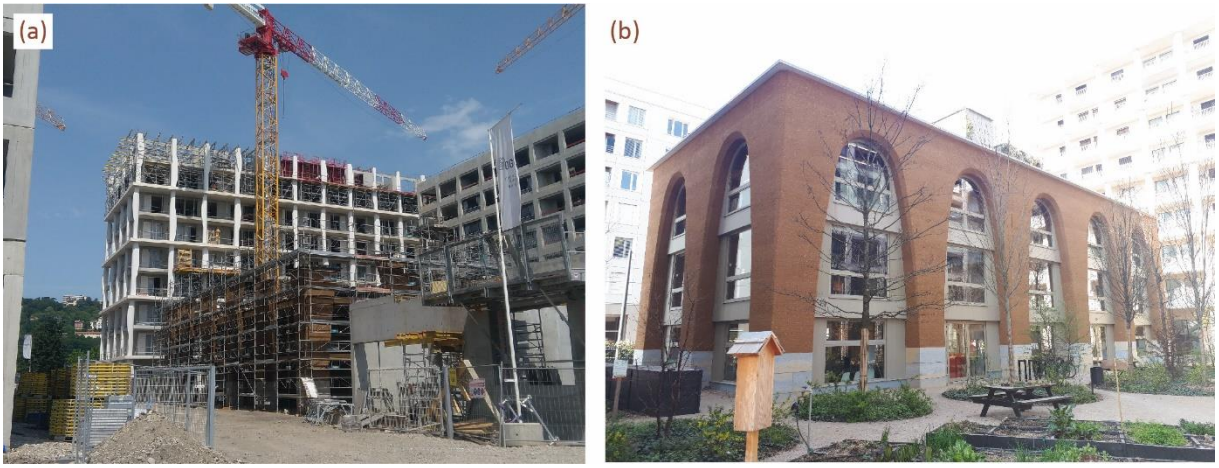

Figure 0.1: (a) Picture of the project taken during construction and my internships; (b) Picture of the finished building (source: author)

2. Environmental and climatic urgency: (re)questioning the place of research in society

How a PhD thesis could be introduced nowadays without (even a quick) reminder of the environmental and climatic urgency? This section will remind us of some insights into the situation along with how it questions the place of research and researchers in society. Indeed, some organisations of committed researchers will be presented leading to a discussion on the notion of neutrality in science. This will help to introduce the potential interest of situated knowledges theory.

2.1. Some insights on the environmental and climatic urgency

Scientists started to alert on climate change and its significant impact on the living quite a long time ago, as witnessed by the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988 or the Meadows Report in 1972 (Meadows et al., 1972). Since then, the IPCC has provided a consensus among the scientific community to argue for actual climate change with anthropic sources. However, no significant change in politics has been observed to reduce this risk. To illustrate, between the first and the last report of the IPCC, 1 trillion tons of CO_2 have been emitted, representing 41% of all CO_2 emissions since 1750 (Figure 0.2).

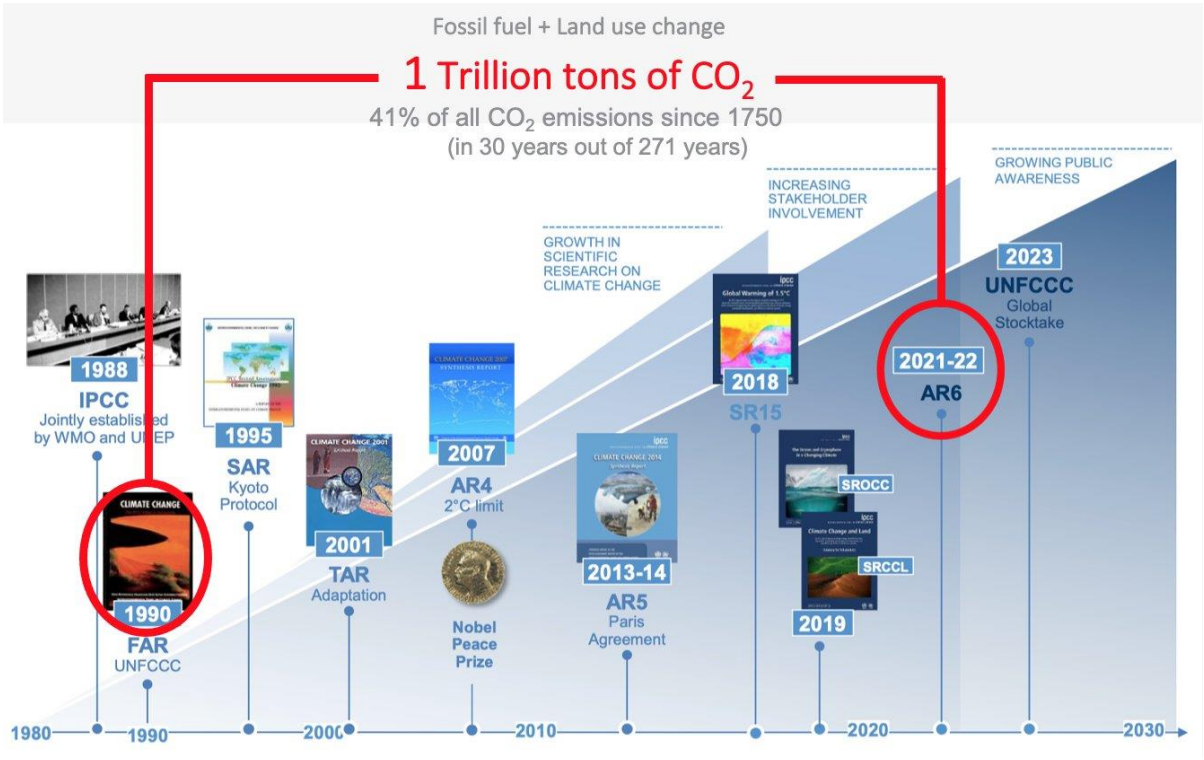

Figure 0.2: Chronology of the different reports produced on climate change (Source: IPCC)

To understand the urgency of the situation, different models, calculations or previsions have been developed, among which the planetary boundaries are commonly cited (Figure 0.3). This model has the advantage of highlighting that human activity does not influence only climate change. Indeed, six planetary boundaries already have been crossed (climate change, green water i.e. water used for plants, biogeochemical flows, novel entities, land-system change and biosphere integrity), whereas other boundaries have not yet been quantified (Wang-Erlandsson et al., 2022).

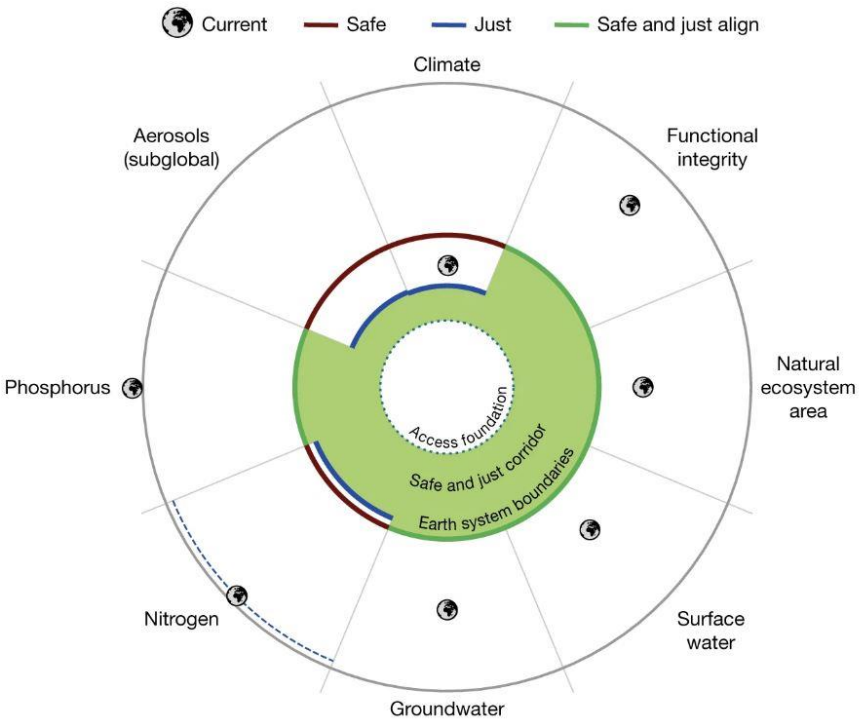

Figure 0.3: Visualization of Earth system boundaries (source: (Rockström et al., 2023))

Such model is interesting to integrate the urgency of the situation. However, as any models, critical distance should be taken, which is brought in particular by the sociology of science and techniques through the question *"Who is deciding on the precise values of boundaries that are to be protected?"* (Biermann and Kim, 2020).

In that context, it seems important to remind some of the principle conclusions established by one of the last IPCC Reports (IPCC, 2021):

- Human influence has warmed the climate at a rate that is unprecedented in at least the last 2000 years.
- Observed warming is driven by emissions from human activities, with greenhouse gas warming partly masked by aerosol cooling.
- Climate change is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes.
- With every increment of global warming, changes get larger in regional mean temperature, precipitation and soil moisture.
- Projected changes in extremes are larger in frequency and intensity with every additional increment of global warming.
- Every tonne of CO_2 emission adds to global warming

Besides, as specified by the IPCC Report, climate change is already affecting every world region, therefore it is already possible to see it or to feel it. For instance, while writing those lines, in July 2023, we already suffered from a heat wave in Europe and new records are observable in the USA (Figure 0.4). This is an important issue when the consequences on human health of such heat waves are significant: authors have estimated that 37 % of deaths related to heat exposure in the world between 1991 and 2018 were caused by climate change (Vicedo-Cabrera et al., 2021).



Figure 0.4: Two tourists take a photo next to an unofficial heat reading during a heatwave in Death Valley National Park, California, on 16 July 2023. (source: AFP (c) Ronda Churchill)

Finally, all these issues need to be thought of in parallel with the fight against inequalities and all oppression systems, when, for instance, we know that climate change will have a considerable impact on migration (Bellizzi et al., 2023).

2.2. (Re)Questioning the place of research and researchers in society

Faced with the unprecedented situation in which humanity currently finds itself (climate change, the collapse of biodiversity, general increase in the consumption of resources, various social and geopolitical issues, etc…), different communities of researchers are trying to act accounting for the urgency. Figure 0.5 represents a timeline of different organizations that will be described in this section. These organizations are not necessarily exemplar; however, they crossed my PhD journey either because I got involved in events or meetings related (Sciences citoyennes, Take back knowledge, Labo1.5), or because I consulted their website and/or their associated bibliography (Ethical committee of the CNRS, Scientist Rebellion, Atécopol). Therefore, it is major to present these organizations as they

have necessarily influenced my research, consciously or not. Besides, this will help the reader to understand the path followed in this manuscript, by understanding *from where*[7] this manuscript is written.

During the last couple of years, researchers have taken positions in the public debate from different perspectives: calling for citizens' rebellion while observing the inaction of governments toward the climate and ecology urgency[8]; denouncing TotalEnergies for instrumentalizing the GIEC Report[9]; or arguing that ecological crisis should challenge the kind of knowledge science should produce[10]. Besides, a study has recently been carried out through a questionnaire survey among CNRS[11] personnel to investigate their opinion on climate change. When asked the question "*Do you think that the urgent need to tackle climate change calls for far-reaching changes in the way we do our jobs as researchers?*", 47% of respondents strongly agree and 41% agree (n=6342 in CNRS personnel)[12]. This raises the issue of the place and role of research and researchers in society, specifically in the context of climate emergency. Indeed, how this consideration of emergency might transform research in its practices and roles is nowadays subject to debate in the research community. It is also a subject of research currently being carried out by Romain Sauzet, a science philosopher at Centrale Lyon School. In his research, he's trying to identify, from a philosophical perspective, how the environmental emergency influence or transform the research field. For now, he has identified two ways of potential transformation: In the practices of science (choice of research topics, material conditions, etc.); or in its essence and particularly on the founding values (autonomy, organized scepticism, etc.).

This section aims therefore at providing some insights into different groups of researchers thinking about those issues, from the more institutional to the least.

[7] E.g. with which organizations the writer is affiliated.

[8] https://www.lemonde.fr/idees/article/2020/02/20/l-appel-de-1-000-scientifiques-face-a-la-crise-ecologique-la-rebellion-est-necessaire_6030145_3232.html

[9] https://www.francetvinfo.fr/monde/environnement/crise-climatique/tribune-totalenergies-est-tres-loin-de-prendre-en-compte-les-conclusions-du-giec-des-scientifiques-denoncent-l-instrumentalisation-de-leurs-rapports-par-le-geant-petrolier_5645285.html

[10] https://www.lemonde.fr/sciences/article/2023/01/27/enjeux-climatiques-la-recherche-ne-peut-plus-produire-de-la-connaissance-a-tout-prix_6159546_1650684.html

[11] French National Centre for Scientific Research (in French: Centre National de la Recherche Scientifique CNRS)

[12] Source : enquête « Les personnels de la recherche face au changement climatique », Labos 1point5, 2020

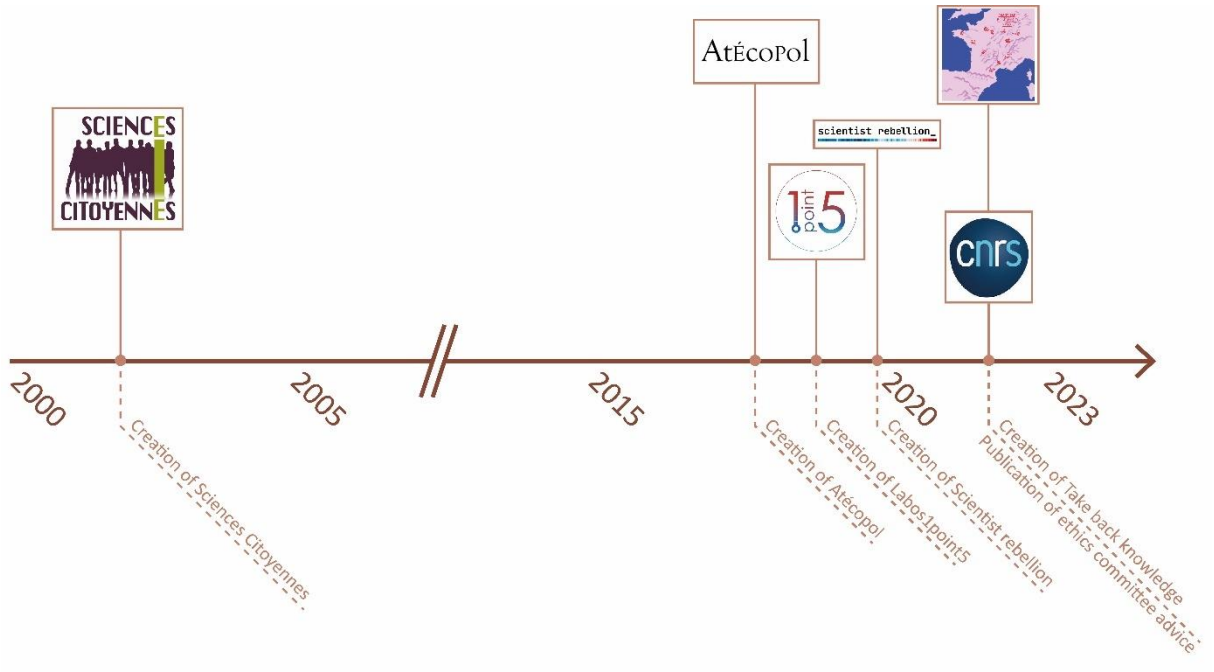

Figure 0.5: Timeline of the creation of different organizations presented in this section (source: author)

2.2.1. Considering environmental urgency: an object of debate in the research community carried by different organizations

The questions raised in this section (2.2) got inspired by different events or works during my PhD thesis. Firstly, I participated in the first seminar "*Journée d'Eté des Savoirs Engagés et Reliés (JESER)*"[13] in September 2022, in Lyon, which represented the starting point of the movement of the same name[14]. During this seminar, different groups were presented, some of which will be described in this section, initiating reflections on knowledge production (scientific knowledge but also non-scientific, in a de-hierarchisation of knowledge perspective). Then, I participated in the first general meeting of the group "*Take back the knowledge!*"[15], which will be described in section 2.2.1.6. Finally, I have worked, in collaboration with another PhD student (Dassibat, Ongoing) from a political and sociological science laboratory to the creation and coordination of a new course designed for 1st year engineering school students. This course[16] aimed to question the relationship between "Ecological and Solidarity Transition" (EST)[17] and research in two different directions, i.e. how research can provide solutions for

[13] Could by translated in English as summer day of engaged and connected knowledge. https://www.ixxi.fr/agenda/seminaires/jeser-2022

[14] https://www.mouvement-ser.org/

[15] https://www.reprisesdesavoirs.org/

[16] 40 hours of courses for about 200 students for one semester.

[17] The term transition could, of course, be debated given the urgency of the situation. However, it has been chosen as it is the term used by French government and as the engineering school depends on it.

EST and how EST questions the role and place of research. Figure 0.6 summarizes the different issues raised during this semester.

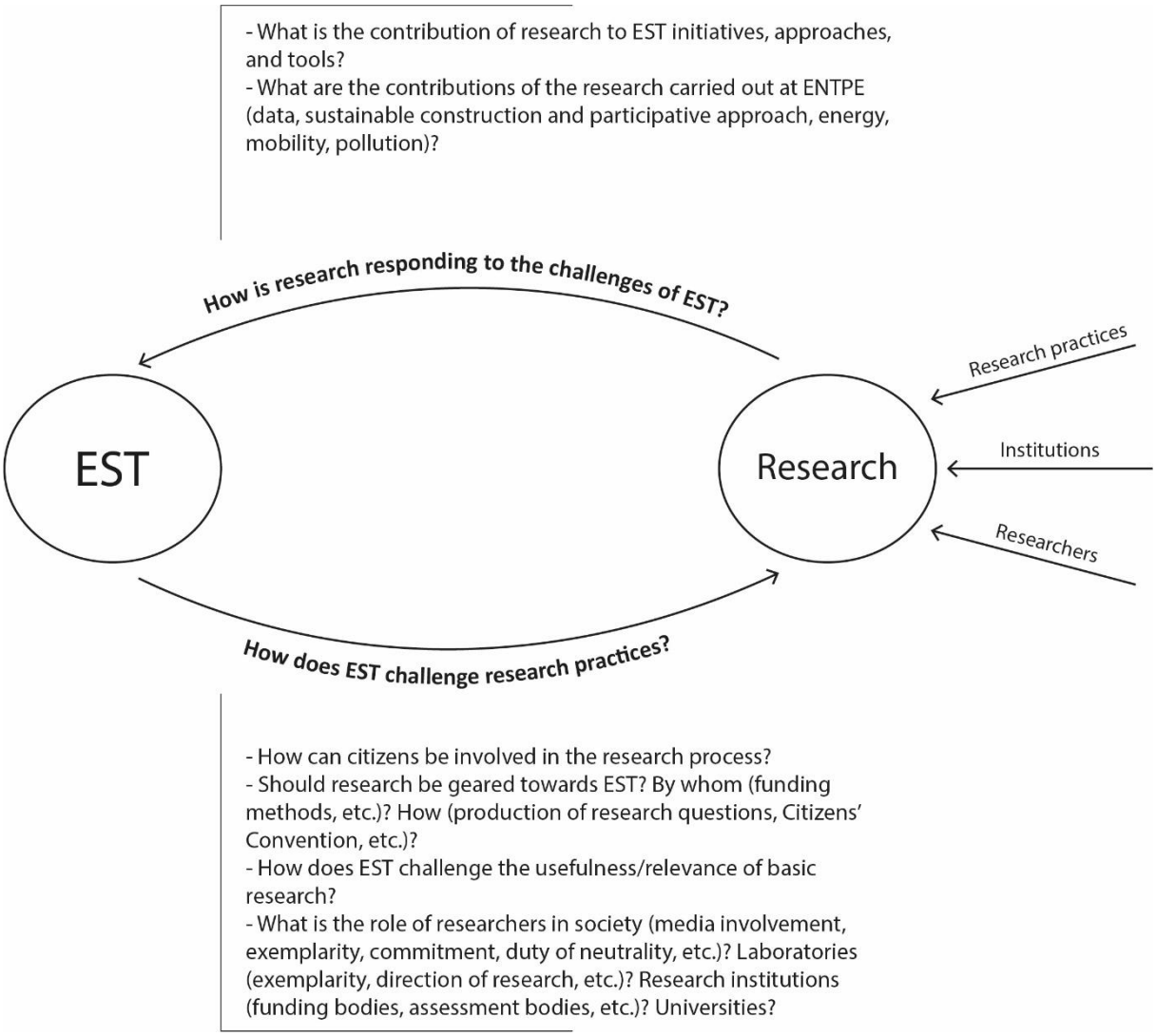

Figure 0.6: Figure representing the questions submitted to students, knowing that those do not have necessarily consensual answers. EST for Ecological and Solidarity Transition.

This work enabled us to present a poster[18] at the first conference organized by Labos 1point5[19] at Sorbonne University and entitled "*Teaching ecological and social transitions in higher education*[20]".

Finally, this section is also based on a presentation made by Kevin Jean[21], an epidemiologist involved in most of the organizations that will now be presented, namely: the CNRS ethics committee advice,

[18] DOI 10.13140/RG.2.2.25798.45123
[19] https://labos1point5.org/
[20] Translated in English by the author. Original version: Enseigner les transitions écologiques et sociales dans le supérieur
[21] https://www.youtube.com/watch?v=vTHeTy_w-lQ

Labos 1point5, ATéCOPOL, Sciences citoyennes, Scientist Rebellion, Take back knowledge!. Finally, a group of PhD student I am involved in will be introduced.

It should be noted that, as I am French and better implented in the French network, most of the research groups presented below are in the French context, which does not mean that similar groups do not exist elsewhere.

2.2.1.1. An ethical issue: CNRS ethics committee advice

In December 2022, the COMETS[22] produced an advice on the consideration of the environmental impact of research from an ethics perspective (Leclerc et al., 2022). This committee thinks about the research field being responsible for accounting for its environmental impact through at least two means: (1) thinking to the mean to limit its environmental impact in practice (e.g. buy better and less, optimise digital use, limit travel and missions, improve the energy performance of buildings); (2) thinking the topics of research and the way to treat them. The committee believes that the second is major because the first, although necessary, is not sufficient given the urgency. Moreover, the field of research has the responsibility to consider the potential use that society will make of its results. However, before establishing any environmental ethics assessment (should this researcher be carried out or not regarding its potential environmental impact?), the committee first argues for a necessary debate between research professionals to address different issues related to the integration of the environmental impact in research practices. For instance, how to reconcile the protection of the environmental with other imperatives of all kinds - human health, training of young people, scientific sovereignty, etc. Should we focus on the near future, by avoiding polluting research, or on the distant future, by focusing on the potentially useful results that this research can bring to the preservation of the environment?

Different groups of researchers already contribute to this debate, in particular, Labo1point5 that have actively worked in collaboration with the CNRS ethics committee to establish this advice.

2.2.1.2. Setting an example: Labos 1point5

This research group, created in 2019, brings together different researchers from various disciplines around a reflection on the environmental footprint of the research field. The group is organized around two axes: one dedicated to the measure and characterization of the environmental footprint of public research in France in terms of greenhouse gas (GHG) emissions. In that context, they have developed a tool allowing laboratories to assess their environmental footprint (Mariette et al., 2022). The second axe is dedicated to supporting and facilitating the transition of laboratories to reduce their

[22] Ethics committee of the CNRS

environmental impact. In that context, since 2021, 22 pilot laboratories are investigated to understand the decision process toward adopted solutions for GHG emissions reduction. Besides, among the group, a team is also in charge of elaborating teaching materials that are open access on their website to diffuse information on climate change and how to tackle it. Finally, they also provide a literature review related to the environmental impact of research.

2.2.1.3. Thinking about upheaval: ATéCOPOL[23]

Since its launch in the autumn of 2018 in Toulouse (France), the *Atelier d'écologie politique* (ATéCOPOL) has contributed to the constitution of a multidisciplinary community of scientists working or reflecting on the multiple aspects linked to ecological upheaval. The aim is to weave links between dispersed knowledge and to reflect on their sharing with the whole society. Then, they work with it on ways of redirecting our trajectory by profoundly modifying the current socio-economic modes of operation. They organized a seminar (accessible on the internet), as well as published texts on political ecology issues and the consideration of environmental impact in research.

Since the impetus given by ATéCOPOL, other similar groups have been created elsewhere in France. EPolar[24], situated in Brittany, can be cited.

2.2.1.4. Develop alternatives: Sciences Citoyennes[25]

Contrary to the other groups presented above, recently created, Sciences Citoyennes is more ancient, founded in 2002 around three axes: democratic decision-making on scientific and technical choices; stimulating responsibility and freedom of speech within research; and increasing civil society's capacity for research and expertise. This group emerged with the critique of the shift from science to "*technoscience"*, the latter designating:

> *« The scientific-industrial complex that goes from the laboratory to the market and vice versa. Nowadays it concerns almost all research activity (research topics and funding)" (Testart et al., 2010, p. 12)[26]*

In their essay, Testart et al. (2010) highlighted that nowadays the ethical issue related to the concept of "*technoscience*" regarding the climate and environmental upheaval would be the lack of control of that technoscience while private interest could be more and more prominent, leading to negative

[23] https://atecopol.hypotheses.org/
[24] https://epolar.hypotheses.org/
[25] https://sciencescitoyennes.org/
[26] Translated from French to English by the author. Original version: "*Le complexe scientifico-industriel qui va du laboratoire au marché, et réciproquement. Il concerne aujourd'hui presque toute l'activité de recherche (thématiques et moyens disponibles)* "

consequences for all society. Different projects of "*geoengineering*"[27] carried out by billionaires individuals such as Bill Gates or Elon Musk are good examples of potential drifts of technoscience, where the risk of such technology are difficult to evaluate and might be catastrophic ("Conférence/débat," 2023). To counter this, Testart et al. (2010) propose to integrate citizens into the decision process that leads to the creation of research topics. In this context, the main aim of Sciences Citoyennes is to "*support the current movement of citizens and democrats reclaiming science, to put it at the service of the common good*" (See the charts, in French, here https://sciencescitoyennes.org/l_association/).

2.2.1.5. Disobey: Scientist Rebellion[28]

The first groups presented above are institutional in the sense that they use common scientific research tools to carry out their actions: seminars, publications, etc… However, other groups of researchers have used a new tool since 2020: civil disobedience. Indeed, Scientist Rebellion, close to Extinction Rebellion[29], is an international organization of scientists willing to raise awareness among citizens about climate change through the use of non-violent civil disobedience actions.

The website provides insights on why choosing such type of action for scientists:

> *"**Why we rebel?***
>
> *Scientists have spent decades writing papers, advising governments, briefing the press: all have failed. What is the point in documenting in ever greater detail the catastrophe we face, if we are not willing to do anything about it?*
>
> *Academics are perfectly placed to wage a rebellion: we exist in rich hubs of knowledge and expertise; we are well connected across the world, and to decision-makers; we have large platforms from which to inform, educate and rally others all over the world, and we have implicit authority and legitimacy, which is the basis of political power. We can make a difference. We must do what we can to halt the greatest destruction in human history."*[30]

In May 2023, a campaign of this organization led to different actions, with different targets, including TotalEnergies and their project of the installation of a floating LNG (Liquefied Natural Gaz) terminal at

[27] The term geoengineering refers to the discipline aiming at manipulate or modify the earth climate and environment at a large scale.
[28] https://scientistrebellion.org/
[29] Extinction Rebellion is a group using civil disobedience to raise awareness on climate urgency. Scientist Rebellion, using similar methods, has the particularity of gathering scientists. https://rebellion.global/
[30] https://scientistrebellion.org/

Le Havre; or BNP Paribas and their support to fossil energies, through a speech at the general assembly of this bank company (Figure 0.7).



Figure 0.7: Picture on the left: action taken against TotalEnergies; Picture on the right: speech at the general assembly of BNP Paribas (source: https://scientifiquesenrebellion.fr/actions/ consulted in July 2023)

One could argue that such actions are beyond the roles of researchers, however, scientific articles emerged recently advocating this type of action. For example, the article by Capstick et al. (2022) published in Nature Climate Change argues that: civil disobedience actually works. Indeed, they provide examples of prompted responses from decision-makers to such actions, but also highlight that even the IPCC "*concludes with 'high confidence' that collective action connected to social movements has played a substantial role in pressuring governments to create new laws and policy*". Besides, the participation of scientists in such a movement is considered valuable due to their "*trusted position […] in society*" (Capstick et al., 2022). Finally, Other authors also have provided ethical insights on whether civil disobedience of scientists is justified or not, providing five criteria. Some of these are already being fulfilled for the case of climate change, such as: "*the situation is unjust*"; "*civil disobedience is the last resort*". And others are being fulfilled depending on the action: "*[the] civil disobedience [action chosen] is more effective than harmful*"; "*[the] civil disobedience [action chosen] is the last harmful action*". The latter criterion is dependent on the context of each country or location: "*consideration of the socio-political situation*" (Bennett et al., 2020).

Such a group of scientists is also helpful in supporting other groups as is the case in the French context where the French branch of Scientist Rebellion has brought their support to the group "*Les soulèvements de la terre"* that has recently (in June 2023) been dissolved by the French government (decision rejected by the council of French state in August 2023).

2.2.1.6. Thinking out of institutions: Reprise de savoirs

Another research group to describe is the one called "*reprise de savoirs"* or "*Taking back knowledges!*[31]". This group, created in the summer of 2022, can be considered as outside institutions although it is partly made up of members from different universities. This organization was born out of a critique of knowledge produced within institutions such as universities. Indeed, these knowledges are seen as standardized and selective "expert knowledge" that would be increasingly related to industrial productivism, joining there the critique of "*technoscience"* established by Testart et al. (2010). They will therefore investigate other places (out of institutions) of knowledge production, without falling into science relativism[32] though. For this, they coordinate activities that often link intellectual and manual work, through participative worksites for example.

2.2.1.7. Member of an earth construction group of PhD student

Finally, as mentioned in the introduction, I have been involved in a group of PhD students from different backgrounds (civil engineering, architecture, pedology, anthropology) and different universities (University of Nantes, Lyon, Biarritz, Lilles, Grenoble, Edinburgh, Mines Paris, Architecture school of Rouen). This group gathered around common values and a common theme of research, being earth construction. Different actions were taken: socialising; having discussions around our thesis subjects; participating in (small) earth constructions; and having discussions on our place in research, in society, and our perspectives and involvement in earth construction field. This group also allowed me to understand the different values and tensions associated with earth construction field (some of which will be described in section 4.4.), which convinced me once again of the importance to situate our research.

Finally, all these examples of organisations of scientific (or even non-scientific) researchers are taking a stand in the public debate which might question the *scientific neutrality* or at least the values carried by science and scientists.

[31] This is a voluntary mistake in English: knowledges instead of knowledge. Indeed, this is a way to insist on the plurality of knowledge type and sources.

[32] In the sense of the definition provided by IEP (Internet Encyclopaedia of Philosophy): "Relativism is sometimes identified as the thesis that all points of view are equally valid. […] In epistemology it implies that all beliefs, or belief systems, are equally true." https://iep.utm.edu/relativi/ consulted in July 2023

2.2.2. Rethinking the notion of neutrality of scientists: incorporated values

"In the face of environmental crises, the main risk for the institution is perhaps a lack of commitment" Kevin Jean, 20th of April 2023[33]

As explained by Capstick et al. (2022), one common argument against the involvement of scientists in civil actions and particularly civil disobedience is the potential risk of troubling the integrity of science. Supposedly, "*the legitimacy of scientists is said to rest on their status as impartial, objective or 'neutral' observers, and the idea that science and politics should remain separate*" (Capstick et al., 2022). However, they highlight that this assertion might not be true for two reasons: firstly, the concept of neutrality of science has largely been discussed in recent years[34]; secondly, recent studies have shown that *"the credibility of scientists is not undermined by advocacy"* (Capstick et al., 2022). For instance, a study recently suggested, using a randomized online survey (n = 1235) in the USA that "*climate scientists who wish to engage in certain forms of advocacy have considerable latitude to do so without risking harm to their credibility or the credibility of the scientific community*" (Kotcher et al., 2017).

The supposed neutrality of science derives from the positivist tradition of science, considering that facts and values are uncorrelated. Facts would therefore have an objective existence while values have a subjective status (Daoust, 2018). However, recent research work from philosophy and science studies has shown that it is difficult to advocate this vision of science and neutrality. A recent report published by The University of Lausanne, investigating the commitment of scientists in public debate, can, for instance, be cited:

> *"The notion of neutrality is often associated with the idea of a 'value-free' science isolated from social influences. [...] Recent developments in the philosophy and sociology of science show that such an ideal is not only unattainable but also undesirable, whether in research practices or public discourse. We, therefore, prefer the idea of a quest for objectivity, scientific ethics and transparency of values."*[35] *(Fragnière, 2022, p. 31)*

However, questioning the neutrality of science should not let us fall into relativism: as this report reminds us, scientific research is a highly reliable source of knowledge production, particularly through

[33] « Place of sciences in the transition of public policies", seminar organized by Médecins du Monde, https://www.youtube.com/watch?v=vTHeTy_w-lQ. Translated from French to English by the author. Original version: « *Face aux crises environnementales, le principal risque pour l'institution tient peut-être au manque d'engagement* »

[34] This will be discussed further throughout the manuscript of this thesis.

[35] Translated by the author from French to English. Original version: « *La notion de neutralité est souvent associée à l'idée d'une science « sans valeur » et isolée des influences sociales. […] Les développements récents en philosophie et sociologie des sciences montrent qu'un tel idéal est non seulement inatteignable, mais également indésirable, que ce soit dans les pratiques de recherche ou dans les prises de paroles publiques. On lui préfèrera donc l'idée de quête d'objectivité, de déontologie scientifique et de transparence sur les valeurs.* »

its processes and methods (data collection, reproducibility, peer-reviewing, etc…) which aim at guarantee a form of objectivity (Fragnière, 2022, p. 32).

Still, this report recalls that science and scientists are part of society: either in the political choices of the research organization, the available funding, or by the interests and ethics and social motivations of researchers. If neutrality of science is requestionned, it is therefore interesting to reflect on ways of achieving some form of objectivity. This is actually one of the purpose of situated knowledges theory, that will be described in section 3.

2.2.3. Declarations of values

If values interact with the objectivity targeted by research, they potentially create a bias that need to be pointed out. Therefore, similarly to the declarations of interests that are commonly made in journal articles to notify of any potential bias related to private funding, it is useful to make a declaration of values.

Firstly, the purpose of describing the different groups of research in section 2.2.1 was to specify my position through those groups. Indeed, during my PhD thesis, I became more or less close to any of those, subscribing to their values, or at least most of them, which necessarily influenced my research and in particular the epistemological choice of situated knowledges. As already notified, I participated, to some extent[36], in different events organized by the "*Take back the knowledges"* movement. I also participated in the seminar JESER and I am close to the value carried by Labos1point5. All of this means I am believing that: (1) Environmental upheaval requires systemic and paradigm shifts at all levels and sectors in societies, (2) this shift should be done democratically and go along with (3) fighting against all forms of oppression systems (gender, race, class, human or non-human, disability, etc…). I also believe that (4) scientific research plays a singular role in that shift in producing reliable knowledge that should not be perverted by private or dominant interests[37].

In some perspectives, I could be seen as a *committed researcher*, at least on the way, while "committed" follows the definition provided by the report of the University of Lausanne:

> *"The definition of commitment used in this report is as follows:* ***any public intervention whose content has a normative aspect, i.e. an evaluative or prescriptive stance on moral, political or social issues, can be described as***

[36] This means that I have not actively participated, in particular in the organization. I mainly got involved as a spectator or supporter.

[37] This declaration of values is voluntary quite large because it could be the object of long discussion and my opinion is continuously changing in the details. I have there chosen to summarize in a few sentences the values that I will probably carry during my life.

> ***"committed"**. This definition is narrower than the one used in some of the literature, which includes all types of interaction with the extra-academic world."*[38] *(Fragnière, 2022, p. 31)*

However, it is worth noting that personal bias related to commitment is not necessarily more important among committed researchers than non-committed ones as the latter are therefore only defined by not sharing publicly their values (Fragnière, 2022, p. 25). One could argue that, on the contrary, being transparent about the values carried by the researcher might be necessary for a scientific approach. This will be discussed further in section 3.

Finally, taking part in some of the groups described above does not mean that I adhere to any values carried by those. For instance, although I am feeling close to Scientist Rebellion, I have not participated in any of their actions[39].

2.2.4. Conclusions of the section

This section has spotlighted different groups of researchers taking a position in the public debate concerning, in particular, environmental upheaval. This helped to introduce the matter of considering values in producing research and the interest of making a declaration of values, similar to declarations of interest.

But if our values interfere with our research in some ways, what could we think about the objectivity of scientific knowledge production? And in particular, the production of knowledge in a civil engineering discipline? To provide insights on this question, the concept of Donna Haraway of *situated knowledges*[40], which will be the object of the following section, is useful.

3. The potential of situated knowledges theory

This section aims to give some insights into the situated knowledges of feminist theory to finally introduce the aim of this thesis.

[38] Translated from French to English by the author. Original version: « *La définition de l'engagement posée par le présent rapport est la suivante : peut être qualifiée d'«engagée» toute intervention publique dont le contenu présente un aspect normatif, c'est-à-dire une prise de position évaluative ou prescriptive sur des enjeux moraux, politiques ou sociaux. Cette définition est plus étroite que celle qui est utilisée dans une partie de la littérature et qui comprend tous les types d'interactions avec le monde extra-académique.* »

[39] Yet.

[40] Once again, the mistake on "knowledge" adding a "s" is voluntary, as it is used by Donna Haraway herself in her publications (Haraway, 1988).

3.1. Some insights on situated knowledges: Donna Haraway

3.1.1. A quick and small history of science philosophy

To better understand situated knowledges philosophical theory, it is useful to place it in the history of science philosophy. The reader should be aware though that this section does not aim at describing precisely the history of science and that some shortcuts could be taken for better clarity in this manuscript.

This history can be started from the *modern science* (between 16th century and today) that first carried the philosophical idea of *realism*, that can be surmised by: *scientific knowledge refers to an objective reality that is independent of observers.* Since the 20th century, a new discipline appeared: the science studies, that have precisely the *science and how scientific knowledge is produced* as object of research. This discipline highlighted the social construction dimension of science and scientific knowledge creation, that contradicted the independence between observers and this supposedly *objective reality*. From there, other philosophical views appeared, such as *Post-modernism,* that can be summed up by: *Reality does not exist independently of observers.* Then, Realists blamed post-modernists of relativism (i.e. rejection of objectivity), which led to a clash in 90s known as the *science wars*. It is in that context, that situated knowledges theory developed, rejecting the neutrality carried by realist, but proposing a new form of objectivity from a *partial perspective* (Daoust, 2018). Figure 0.8 represents this historical context.

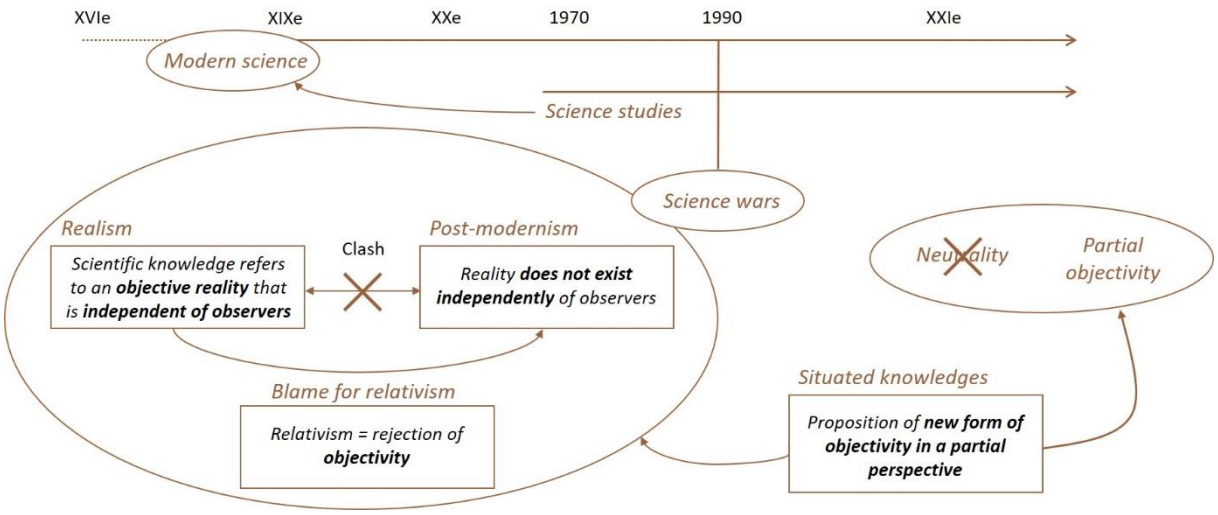

Figure 0.8: Schematic chronology of a history of science philosophies. based on (Daoust, 2018). (source: author)

3.1.2. Feminist roots of situated knowledges

The concept of situated knowledges, has its roots in feminist epistemology and philosophy and is closely linked with the women's political movements of the 1960-70s (NagyHesse-Biber, 2012, p. 47). In the scientific community, we can cite different contributors, from the late 20th century to those movements and theories: Hilary Rose (sociologist of science), Alison Jaggar (philosopher), Sandra Harding (philosopher), or Donna Haraway (historian of science) (NagyHesse-Biber, 2012, p. 47). This movement of thought considers that there is no strict separation between epistemic norms (i.e. norms internal to science, e.g. peer-reviewing, methods of data collection, …) and non-epistemic norms (i.e. norms peripheral to science: ethics, values, etc…) (Daoust, 2018). An example in the discipline of economics could be the historical distinction between wage labour and leisure activities used as epistemological categories to analyse economic phenomena, which have hidden non-wage labour from women (e.g. domestic work) (Daoust, 2018). This is an example of systematic discrimination (in that case toward women, but similar examples can be found considering race, class, etc…) that had consequences on the *objectivity* of science production. Therefore, the concept of situated knowledges is embedded in a context of struggle against systems of oppression that led to a questioning of the neutrality of science:

> *"If groups are systematically discriminated against on the basis of sexist ideologies and the institutions [in our case scientific research institutions] causing these ideologies remain passive, it cannot be claimed that these institutions have a neutral objective"*[41] *(Daoust, 2018)*

As a person identifying myself as a man (therefore being a member of the dominant group when it comes to gender) using feminist concepts for this thesis, I am aware of the risk of reclaiming of feminist struggle that could pursue some sort of domination process. I will do my best and try to constantly think about this issue, in particular by trying to stay honest and modest regarding feminist struggle. Authors have actually pointed out that men can "*educate themselves"* to feminist epistemology and that it is even an ethical and political necessity since those who dominate are just as concerned by domination as those who are dominated by it (Frasch, 2020).

[41] Translated from French to English by the author. Original version: « *Si des groupes sont systématiquement discriminés en vertu d'idéologies sexistes et que les institutions causant ces idéologies demeurent passives, on ne peut prétendre que ces institutions ont un objectif neutre.* »

3.1.3. Position of Donna Haraway: Situated Knowledges (SK)

> *"Vision is always a question of the power to see-and perhaps of the violence implicit in our visualizing practices.* ***With whose blood were my eyes crafted?****" (Haraway, 1988)*

One of the main authors to have conceptualized the notion of situated knowledges is Donna Haraway who published: "*Situated knowledges: the science question in Feminism* and *the Privilege of partial perspective"* (Haraway, 1988). In her essay, Donna Haraway aims to challenge the notion of "objectivity" in science to promote her new scientific doctrine of situated knowledges as mean to increase objectivity. She recalls first, based on the literature of science studies, that all knowledge, including science, is to some extent the result of social construction. In this context, she criticises the modern concepts of science carrying a vision of universalism which tends to standardize or normalize the translation of realities into knowledge in a specific perspective (that of those who dominate):

> *"Science has been about a search for translation, convertibility, mobility of meanings, and universality - which I call reductionism only when one language (guess whose?) must be enforced as the standard for all the translations and conversions" (Haraway, 1988)*

To establish her critique, she uses the vision, the look, and the view, as metaphors for scientific practices. From a positivist perspective, the vision would therefore be out of reality, exterior to the object that it observes and describes, and therefore is neutral and objective. However, she denies this possibility of being *outside of reality* and instead believes that the image of the external observer is a way to perpetuate oppressive systems. Therefore, she defends a principle of *partial perspectives* of the vision, assuming that the latter is actually embedded in realities[42]. In other words, the researcher who observes a phenomenon (of any type: social, natural, physical…), is part of the social realities that necessarily bias its vision. Thus, to reduce those biases she maintains that it is necessary to assume this *partial perspective* of the vision by situating, in particular, the bearer of this vision and the knowledge produced accordingly. Doing so, the research produced could be, consciously, *situated knowledge*. Finally, she advocates the concept of partial perspectives consideration as a way to improve the rigour and quality of the science produced.

For better clarity, a clear distinction should be made between the terms "*contextualise*" and "*situate*". From a realism perspective, the researcher, necessarily carrying values as being part of the society, observes an object of study with a method. However, realists consider that there is no interaction

[42] While from a positivist perspective there is a single reality that can be observed, in situated knowledges there are multiple realities depending, particularly, on social context.

between the values of the researcher, the object of the study and the method. From this perspective, it is possible to provide elements of the context of the study (e.g. where it was performed or carried out), or of the research (e.g. declaration of interests, who provided the grant, etc…). From a situated knowledges perspective, interactions between the values of the researcher the method and the object of the study are now considered. Similar elements of context should be provided, but they are not sufficient to (explicitly) *situate* the research and researcher. However, it is the reflexivity of the researchers on the interactions between their values method and the object of the study that is necessary to situate. In other words, the more the reflexivity on values, the more explicitly and consciously the researchers situate themselves or their research. Figure 0.9 represents this distinction between contextualising and situating.

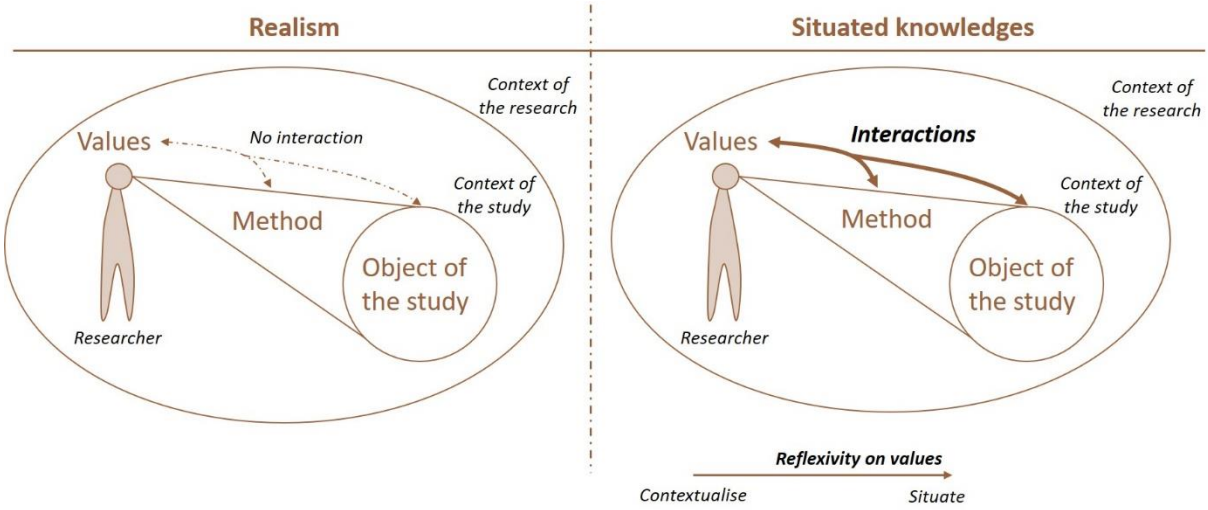

Figure 0.9: Scheme representing the differences between the philosophical approaches of realism and situated knowledges, highlighting the distinction between contextualising and situating.

3.1.4. A concept now commonly used in social sciences and beginning to be used in natural sciences

Since its conceptualisation, the principle of situated knowledges has been widely used in social science disciplines (In France, see for example the work of Benedikte Zitouni (Zitouni, 2017)). But it also has been involved in disciplines "*in which the objects of study can have both social and natural features, such as medical, environmental and archaeological research*" (NagyHesse-Biber, 2012, p. 47).

Besides, researchers from natural and physical science disciplines have started to look at this theory. The chemist Alessandra Quadrelli is one of the pioneers to have implemented such a theory in her research within her discipline, willing to develop a concept of *situated chemistry*. She has indeed

provided five public courses, in early 2023, in Lyon about this topic available on the internet[43]. She also animated a seminar called "*Situated Science: political values of scientific approach?" [translated from French by the author]*, in the University of Lyon, with scientists of various disciplines including anthropologists, physicians, or sociologists[44].

This growing interest in the scientific community on situated knowledges probably means that it has advantages to any research. Indeed, such a theory is believed to increase the objectivity and reflexivity of the scientific approach.

3.2. Opportunity to gain in objectivity, rigour and reflexivity

"non-situated knowledge is situated knowledge that ignores itself" *Alessandra Quadrelli*[45]

According to Alessandra Quadrelli, there are two interests related to the situated knowledges: the first is political because non-situated knowledge ignores the bias of its perspective and then perpetuates injustices that are in favour of the interests of those (individuals or systems) who benefit from this bias. The second is from an epistemological perspective because it makes it possible to identify the limits of the knowledge produced, which improves the rigour of the scientific approach.

Therefore, situated knowledges theory, by aiming to identify the biases that reside in the hidden values carried by research systems and individuals, is a useful tool to take the quest of objectivity further. Indeed, "*Maximizing objectivity has usually been taken to require maximizing the social neutrality of research methods"* (NagyHesse-Biber, 2012, p. 60), where maximizing the social neutrality can be understood as minimizing biases of research methods. Therefore, good research methods should identify (or at least allow the reader to identify) potential biases related to the values, assumptions and interests of the researcher who carried out this method. Thus, if a different researcher or group of researchers find different results applying the same method, the differences will easily be identified lying in the values and assumptions. However, if these social values, assumptions and interests are shared by the entire discipline or field of research, they might not be identified. So, "*starting off research from 'outside' such a field, discipline, or society – even from just a little bit outside, such as on the margins – can enable the detection of the dominant values, interests, and assumptions in existing*

[43] 1. https://www.youtube.com/watch?v=gpDhpgy2U9g 2. https://www.youtube.com/watch?v=_I7S_4b1mPQ 3. https://www.youtube.com/watch?v=xrsa49q6UVg 4. https://www.youtube.com/watch?v=ASJyzP75LsA 5. https://www.youtube.com/watch?v=5g7Z0O1ikUs

[44] https://ecoleanthropocene.universite-lyon.fr/la-science-situee-valeur-politique-de-la-demarche-scientifique-seance-1-2-288794.kjsp

[45] Quotation of Alessandra Quadrelli at 44min of her following course: https://www.youtube.com/watch?v=gpDhpgy2U9g; Translated from French to English. Original version: « *Un savoir non-situé est un savoir situé qui s'ignore* »

knowledge claims" (NagyHesse-Biber, 2012, p. 60). Thus, not only situated knowledges can help to improve objectivity, but some authors even consider that it should be a claim:

> *"It is, therefore, necessary to assert that **feminist struggles have allowed and still enable the development of more objective visions** than those that prevailed until now in both the secular and scientific world. And this claim can and should be made not only at the global social level but also at the level of specific scientific disciplines."*[46] *(Frasch, 2020)*

Finally, following a situated knowledges theory is a matter of reflexivity. Indeed, researchers should "*recognize, examine, and understand how their social background, location, and assumptions affect their research practice*" (NagyHesse-Biber, 2012).

Once the advantages of following situated knowledges theory are understood, it is interesting to see what it could bring to the civil and mechanical engineering discipline, which is the aim of this thesis.

3.3. Aim of the study: toward a situated civil engineering study

The route of the PhD thesis began with a civil engineering project related to a technical issue that arose from an actual construction project. As explained in the introduction, after working on this project for a year and engaging in discussions with various stakeholders, particularly the mason, I realized that (1) technical problems represent just the tip of the iceberg, and (2) these technical challenges are intertwined in socio-political realities. Consequently, conducting research focused on technical aspects could have both positive and negative implications within socio-political realities. This realization generated a sense of responsibility that intersects with the values I hold and detailed in section 2.2.3. From this, I felt the need to *situate* the first knowledge (in civil engineering) I had produced, for which the concept of situated knowledges was helpful.

A distinction between "situated knowledges" and "situated research" can be drawn for this thesis. On one hand, situated knowledges theory teaches us that any knowledge is situated, the importance is to know if it is consciously or not. Since I was not initially acquainted with the theory of situated knowledges when I embarked on my PhD journey, the preliminary work undertaken, addressing the civil engineering research question (as described in section 5), was merely consciously situated. Therefore, the primary objective of this thesis is to situate this initial research, thereby transforming the knowledge created into a situated one (I.e. consciously situated). On the other hand, situated

[46] Translated from French to English by the author. Original version: « Il est donc nécessaire de revendiquer le fait que les luttes féministes ont permis et permettent encore d'élaborer des visions plus objectives que celles qui avaient cours jusqu'alors dans le monde profane comme scientifique. Et cette revendication peut et doit être portée non seulement au niveau social global, mais aussi au niveau des disciplines scientifiques particulières. »

research could be adopting an epistemological perspective that keeps in mind the situated nature of any resulting knowledge.

Hence, the aim of this study is to reflect on the usefulness of the theory of situated knowledges by situating the civil engineering knowledge produced at a first stance and trying to adopt this epistemological position for situated research. In doing so, this thesis attempts to establish a contribution to the possibility and the interest of integrating such an approach in the natural and physical sciences, similar to the reflections carried out by Alessandra Quadrelli in the discipline of chemistry. Hopefully, this will help to improve rigour and objectivity in these disciplines.

As explained in the introduction, these reflections stemmed from my experience in the field of earth construction. I observed that existing controversies might hinge on differing values held by researchers. Additionally, I sensed that values are sometimes embedded in the introductions of journal articles and obscured by hypothetical "barriers" to earth construction. To explore these hypotheses more thoroughly, it becomes essential to introduce the reader to the field of earth construction.

4. Introduction to earth construction and architecture

This section will introduce the reader to earth construction, first providing insights on the environmental and social impact of mainstream construction, then describing what can be defined as "earth construction" and understanding its potential advantages considering the construction impact. Finally, some controversial topics will be highlighted and a discussion will introduce the second research question of the study.

4.1. Environmental and social impact of mainstream construction: some insights on the current situation

The architectural, engineering and construction (AEC) sector is one of the most impactful on the environment, with 37% of energy-related carbon dioxide emissions, of which the construction industry accounts for a quarter of these emissions (UNEP, 2021). While improvements have been made in reducing carbon dioxide emissions from the service life of buildings[47], the proportion of embodied carbon emissions is growing in the AEC sector, mostly due to the increasing use of carbon-intensive materials[48] (cement, steel, rock wool among others) (Giesekam et al., 2014). Indeed, the consumption of carbon-intensive materials has constantly grown during the 20th and the beginning of the 21st centuries (Figure 0.10). In the UK, cement and steel (the main component of concrete material which

[47] i.e. the energy consumed by heating and cooling buildings during their life.

[48] Carbon-intensive materials should be understood as materials with high embodied carbon dioxide emissions, i.e. high emissions due to the extraction, production, use, and destruction or recycling.

is the most widely used in construction) contributed in 2012 to 44% of industrial carbon emissions (Allwood and Cullen, 2012, p. 13). Cement alone is responsible for 5% (Chaturvedi and Ochsendorf, 2004) to 8-9% (Monteiro et al., 2017) of the world's CO_{2eq} emissions.

However, like every sectors, the AEC sector requires to decrease its environmental impact and one way to do so would be to reduce the use of these carbon-intensive materials. The strategy of improving the environmental performances of these materials is often investigated, such as for concrete (Blankendaal et al., 2014; Kim et al., 2016). However, authors consider necessary the use of alternative low carbon emissions materials (timber, straw-bale, hemp, bamboo, earth among others) (Giesekam et al., 2014). Therefore, Earth material for construction seems to be an opportunity to reduce, to some extent, the environmental impact of the AEC sector.

The social implication of mainstream construction should not be hidden, although it won't be detailed in this thesis. For more insights on this topic, the research of Jounin (2009), for instance, can be consulted. During one year, the author was involved in the daily life of reinforced concrete construction sites in Paris where he investigated the poor working conditions of builders due in particular to the increasing use of subcontracting and temporary work: interiorization of workers subject to these regimes, division of workers' collectives, illegal practices by employers, contradictions weighing on safety at work, massive recourse to a weakened foreign workforce, racism and discrimination, etc… (Jounin, 2009).

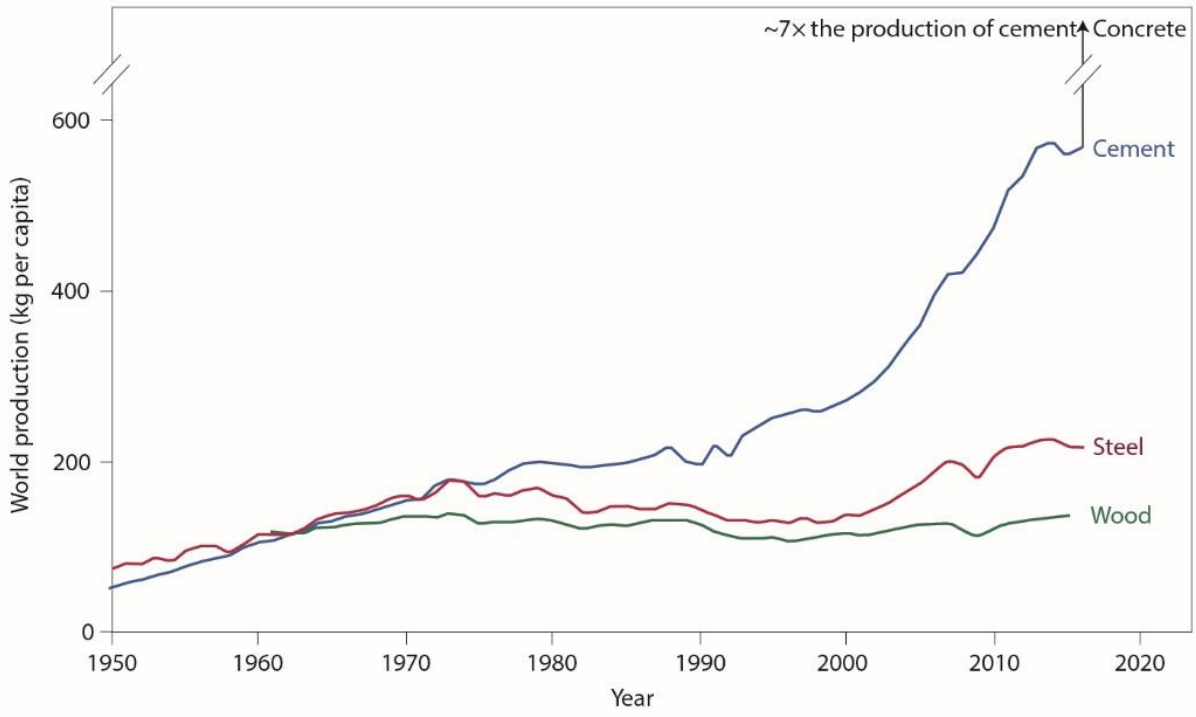

Figure 0.10: Historical growth in production of infrastructure material (cement, steel and wood) per capita (source: (Monteiro et al., 2017))

4.2. What is earth construction?

4.2.1. An ancestral construction material

Earth material is probably one of the oldest construction materials used in human history, in various locations in the world. As an example, different demonstration buildings can be found in very diverse geography and history, such as some parts of the great wall of China (Figure 0.11a); The castle of Alhambra in Grenada in Spain, built in the XVe century (Figure 0.11b); the town of Shibam in Yemen, built during XVIe century with seven-storeys buildings, sadly threatened by wars (Figure 0.11c); or the great mosque of Djenné in Mali, first built during XIIIe century and rebuilt at the beginning of the XXe century (Figure 0.11d). Earth materials and techniques for construction have therefore been developed in a great variety of cultures on all continents. And it is present in many locations (Figure 0.12). Indeed, there are still (in 2020) about 10% of people living in houses made with earth material (Marsh and Kulshreshtha, 2021), while it was around 30% in the 90s (Houben and Guillaud, 1994). This decrease is mainly due to rural exodus in low-income countries (Marsh and Kulshreshtha, 2021).

In France, there is an important heritage of earth construction, that can be found in different regions such as Brittany or Auvergne Rhône-Alpes. Concerning the latter, a recent PhD thesis has been defended (in June 2023) having studied the earth construction heritage in Lyon and its surroundings, based on a corpus of 750 earth buildings, among which 365 were located in the city of Lyon. The author has highlighted that, contrary to popular belief that earth constructions are mainly rural constructions,

many earth buildings in the region are remarkable (castles, hospitals, …) or are high buildings (until six storeys) (Mille, 2023). While such construction was widespread before the beginning of the 20th century, this process of construction disappeared in the middle of the 20th century to finally reappear now at the beginning of the 21st century with a new interest, notably due to the potential low environmental impact of earth material. For more insights into the socio-history of earth construction in France, the thesis of Victor Villain can be consulted (Villain, 2020, pp. 34–88).



Figure 0.11: (a) Castle Alhambra in Grenada, Spain (source: National Geographic - WillSelarep, stock via Getty images); (b) City of Shibam, Yemen (source: (Leiermann, 2021)); (c) Mosque of Djenné, Mali (Source: (Sacko, 2021)); Great wall of China, China (Source: (Preciado et al., 2017))



Figure 0.12: Map of the traditional earth construction regions around the world including locations of the UNESCO world heritage sites ("CRAterre :: Galerie des images," 2023)

4.2.2. Which earth, which techniques?

This section will highlight that it exists a great diversity of earth, therefore, along with the variety of cultures in which earth construction techniques have taken form, it resulted in a great diversity of techniques and implementation processes. Even the word earth in itself has various meanings. Therefore, it is useful, firstly, to define the term *earth* that will be used in this thesis.

4.2.2.1. Earth, earth, clay, soil, which earth are we talking about?

The word "earth" has different meanings. From the old English "eorpe", it can relate either to a land ("country", "district") or the soil ("ground", "dirt", "dry land"), but it is also used to describe the "material" world as opposed the underworld (heaven). There is then a relation between the livings (opposed to the deads) and the "earth"[49]. Here, it is the "ground" meaning that is considered, so the "*loose substance of which a large part of the surface of the ground is made, and in which plants can grow*"[50]. Earth, therefore, both carries and contains livings. In our case, earth material for construction is more specific than that. However, one should be aware that it might not be seen only as a resource for human purposes since it is also a living world that we should care about. While different words can be used (such as soil), in a matter of clarity, in all the manuscripts, the word *earth* will be preferred.

The "loose substance" called earth is the result of a very long process named pedogenesis. The first step is the alteration of the bedrock by the climatic and environmental conditions (rain, temperature variations, freeze-thaw, plant growing, …) which desegregate and alter the bedrock into smaller particles. This has two results: unaltered grains (stones, gravels, sand, silt) and chemically altered particles (clay and minerals), both forming a paste, that will then be colonized by fauna and flora. The latter will continue the alteration of the grains (Houben and Guillaud, 1994).

The earth commonly chosen for earth construction is a clayey part of this *loose substance*, that is generally under the vegetal earth used for agriculture as can be seen in Figure 0.13.

[49] https://www.etymonline.com/word/earth#etymonline_v_941

[50] https://dictionary.cambridge.org/dictionary/english/earth

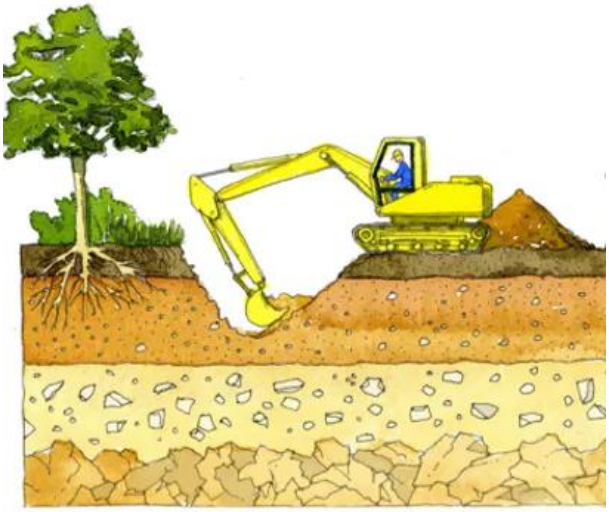

Figure 0.13: This figure represents the different layers from the rock to the vegetal earth. The earth generally used for construction is the one under the vegetal ones. (source: extracted from © Arnaud Misse)

4.2.2.2. Diversity of earth

Earth is a granular material that is composed of different sizes of grains from the smallest (the clay) to the biggest (the gravel), with silt and sand in between. Great variety in the proportion and nature of those grains are observable which makes the *resource* earth very diverse and heterogeneous. As a representation of this diversity of the proportion of the grains, we can for example look at the work established by Rojat et al. (2020), that have investigated 23 different earths collected in earth building heritage in France and represented by their grading curves (Figure 0.14).

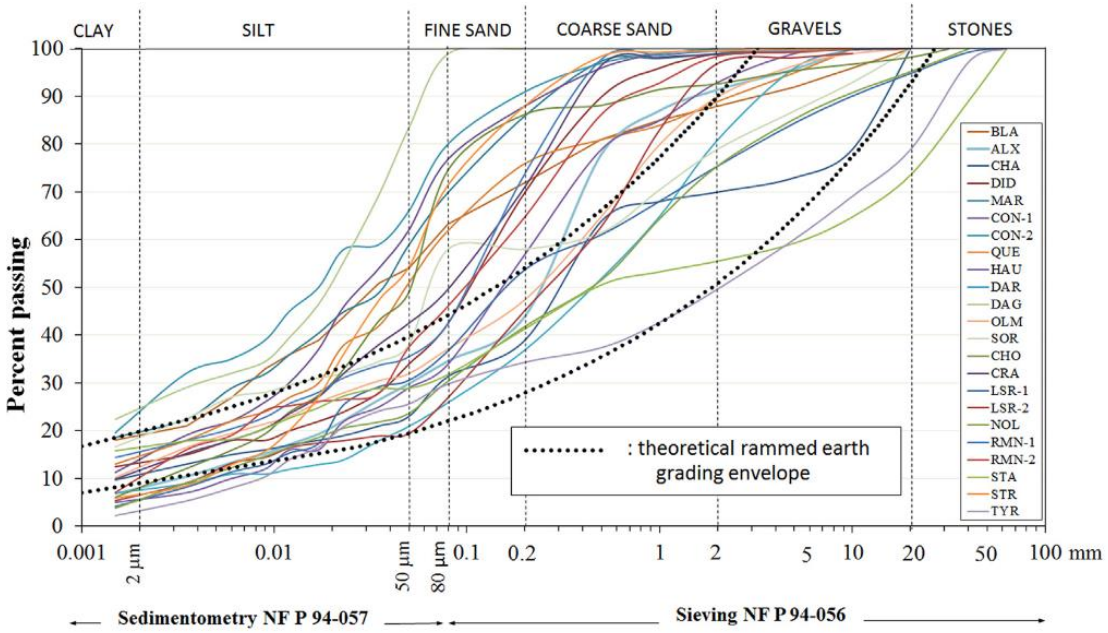

Figure 0.14: grading curves of 23 different earth extracted from earth heritage buildings in France compared with the theoretical rammed earth grading envelope from Houben and Guillaud (1994) (Source:(Rojat et al., 2020))

Due to the diversity of earth and culture in which techniques were developed, there is a diversity of implementation techniques.

4.2.2.3. Diversity of techniques

Earth construction is a wide domain that covers different techniques and processes along with different use. According to the technique and the earth (the amount of fine parts, clay and silt), a different amount of water (corresponding to the manufacturing water content) will be added to the earth. Fibres, such as hemp or straw can also be mixed into the earth. Sometimes, *stabilisers* (i.e. hydraulic binders) can also be added, such as cement or lime, but this will be quickly discussed in the section 4.4.1. Figure 0.15 summarizes some of the most common techniques.

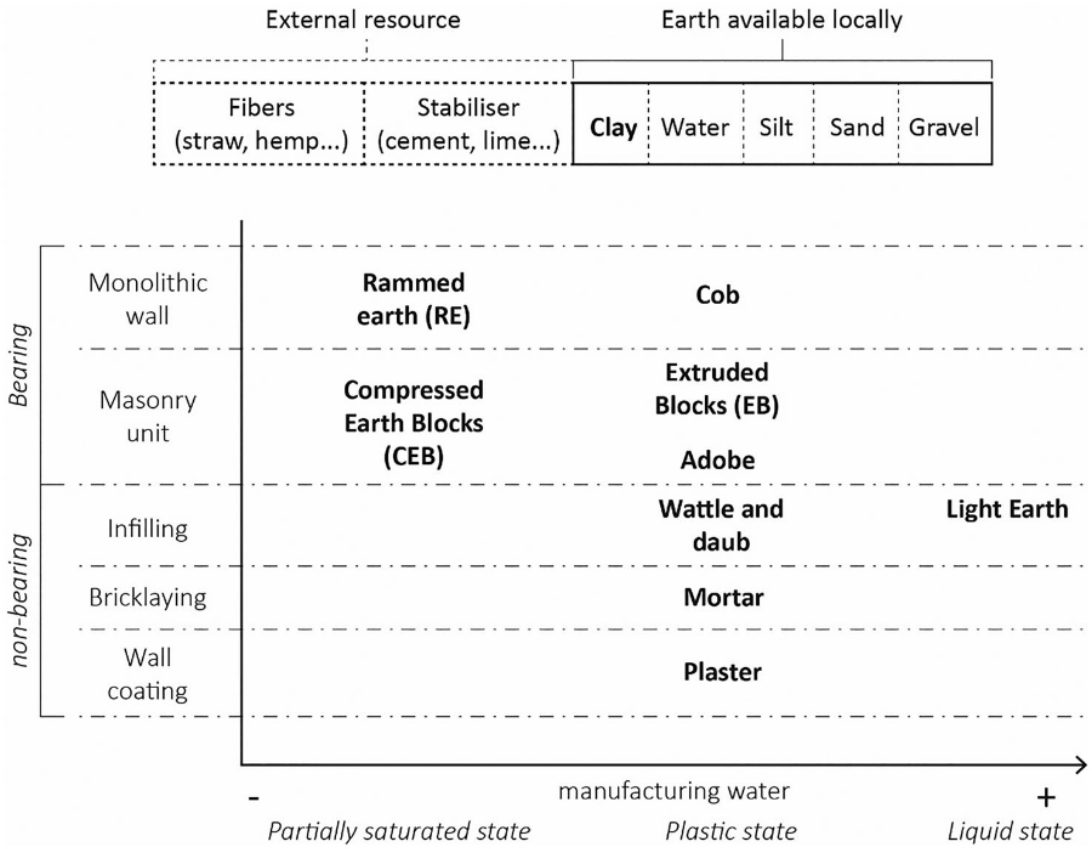

Figure 0.15: Description of the techniques of earth construction according to the amount of clay and the building components (source: (Pelé-Peltier et al., 2022b))

To read a description of each of these techniques, see for example chapter 1 of the thesis of Soudani (Soudani, 2016, pp. 40–56).

The technique on which we focus for this thesis is *rammed earth*. The principle is to ram successive layers of earth in-between formworks to build a monolithic wall. The earth *"must be prepared to the right water content in order to be wet enough to ensure a good consistency but not too much to prevent*

cracks formation when drying or weaken compaction ability" (Soudani, 2016, p. 47). A representation of the rammed earth construction process is proposed in Figure 0.16.



Figure 0.16: rammed earth construction process. This is a representation of traditional rammed earth (with wood ram and wood formwork). In recent implementations, different degrees of mechanisation of the process can be found. (© Arnaud Misse)

Similarly, to the other techniques, rammed earth has disappeared from the construction field for years. But it is now reappearing with more and more modern buildings built with this technique (Figure 0.17). This is explained in particular by the various advantages that this technique represents for the construction field, which now will be discussed.



Figure 0.17: (a) Private house in Marseilles, France, 2020 (source: Le pisé, architects: Marine Bonnefoy); (b) School in Brangues, France, 2018 (Source: Le pisé, Architects: Landfabrik)

4.3. Potential advantages of earth construction

Earth construction can represent different opportunities for the construction sector, which will be quickly described in this section. Besides, during my PhD thesis, earth material also represented an opportunity for me which is important to highlight as well.

4.3.1. Opportunity for the construction sector

First, earth material, as a locally available material represents an opportunity in terms of lowering the environmental impact of the construction sector. Indeed, it already has been demonstrated that the use of local materials reduces considerably the amount of embodied energy used for construction

(Morel et al., 2001). Indeed, it has been observed in the literature that "*all references comparing wall material to conventional materials at the building scale, find better environmental performances of earthen walls compared to fired brick walls"* (Anne Ventura et al., 2022). However, one should be aware that the environmental impact will also depend on the design choices and local situations, in particular, transportation. Moreover, the use of hydraulic binders mixed with earth material can increase significantly the environmental impact of earth material (Anne Ventura et al., 2022).

Then, upcycling earth from excavation work, or using it from landfills, is a valuable optimization of waste into construction materials. Indeed, excavated earth represents an enormous amount of available resources for the AEC sector. For instance, in Brittany, 2.8 million tons of earth were landfilled in 2012, where at least 23% could have been used for earth construction to build about half of the single-family dwellings required in the region that year (Hamard et al., 2018). Therefore, earth construction could represent an opportunity for the shift from linear to circular economy[51] in the construction sector, keeping in mind that there are different ways, more or less circular, to build with earth (Pelé-Peltier and Goizauskas, Under review). In terms of circularity, the advantage of earth material relies on the reversibility of the clay binding forces with water *"allowing earthen materials to be plasticized and reused without very little energy input such as heating, chemical stripping or mechanical methods of processing*" (Ben-Alon et al., 2020a).

Besides, earth materials and techniques present interesting thermal performances in particular "*good summer thermal performance by passive means"* (Zawistowski et al., 2020) and interesting thermo-hygro-mechanical properties, which can *"contribute to the reduction of the environmental impact of buildings during construction and service life*" (Fabbri et al., 2018). Related to these properties, earth material can also have benefits on indoor air quality, in particular by naturally regulating the relative humidity (Ben-Alon et al., 2020a) and represents a great potential for the reduction or regulation of interior pollutants. On the latter, there is an on-going PhD thesis investigating the potential of earth plaster to regulate the amount of CO_2 in the interior (Arris-Roucan, on-going; Arris-Roucan et al., 2023).

Finally, it can also be argued that earth material for construction could have socio-economic benefits. Some authors highlight for example the potential of job creation (Zami, 2020a), and therefore can provide local employment opportunities enhancing local economies (Ben-Alon et al., 2020a), although

[51] Circular Economy (CE) is a concept for which a definition have not yet achieved a consensus among scientific community, although among 221 definitions, many mention that a fundamental shift is required for CE (Kirchherr et al., 2023). For this thesis, the definition provided by Figge et al. (2023), has been chosen as it introduces a notion of imperfection in the applicability of the concept: "*The circular economy is a multi-level resource use system that stipulates the complete closure of all resource loops. Recycling and other means that optimise the scale and direction of resource flows, contribute to the circular economy as supporting practices and activities. In its conceptual perfect form, all resource loops will be fully closed. In its realistic imperfect form, some use of virgin resources is inevitable."* (Figge et al., 2023)

it depends on the local socio-economic context. Besides, some authors remind us that earth construction methods are often "*applied as a community engaging activity*" (Ben-Alon et al., 2020a), which will be one of the points of the next section. Figure 0.18 illustrates such a possibility of community-engaging activities.



Figure 0.18: Children participating in the construction of their future school (source: belenfantdaubas.org)

4.3.2. Earth construction opportunity for me as individual

One advantage of earth construction that I truly feel is the easiness to participate in the construction site. Indeed, during my PhD thesis, I had different occasions to participate in different types of construction (from small ones as furniture to bigger ones as the construction of a school extension). This was the opportunity to *put the hands in the earth* so that it sometimes helped to reflect through spending enriching collective moments. Finally, I offered a similar opportunity to students by organizing a small participatory work camp myself, in which around a hundred students got involved at different times. See Figure 0.19 for some of the constructions I have participated in.



Figure 0.19: (a) Construction of a place of meditation on the pilgrimage route to Santiago de Compostela, Montverdun priory, base made with rammed earth and wood structure, the construction was temporary and meant to stand for a year (source: author); (b) Construction with ENTPE students of a garden sheds for inhabitants (source: author)

4.4. Controversies in earth construction field

It exists different controversies in both scientific and professional communities in earth construction field. Some are related to the use of admixtures such as cement or lime (commonly called stabilisers), and others are related to the development of new techniques, such as 3D printing. Additionally, premanufacturing earth wall assembly has also been cited by Soudani (2016), reminding us that care should be taken in the distance between the construction site and the factory to maintain the environmental virtues of the material (Soudani, 2016, p. 50).

4.4.1. Adjuvantation (or stabilisation)

In scientific literature, the word “stabilisation” is generally used to refer to cement or lime adjuvantation. However, it can be considered to create confusion by distinguishing between a “stabilised” and “unstabilised” form of earth material. In this thesis, the word “adjuvantation” referring to the addition of an external material (commonly cement or lime), not being naturally present in the earth, will be preferred.

Various reasons can bring professionals to use lime or cement adjuvants in their material. There are technical reasons, to improve the mechanical performances of the earth material and to lower its water sensitivity (Ouedraogo, 2020). Adapting an earth to a previously selected technique can also be a reason: for instance, some authors have highlighted the need for hydraulic admixture when the granulometric and clay content is not suitable for Compressed Earth Blocks (CEB) (Dorado et al., 2022). However, one could argue therefore that is necessary to adapt the technique to the local earth to avoid this issue. The need for hydraulic adjuvantation is also due sometimes to a matter of standards or regulations, indeed, adding admixtures can help using existing concrete codes for earth construction while there is a lack of such codes for earth material (Delgado and Guerrero, 2006). Adjuvantation also has been described as required to convince clients and insurance offices to build with earth (Marsh et al., 2020). We see therefore that the matter of adding a hydraulic adjuvant for earth is not only a technical issue.

This is however a major concern as the use of hydraulic adjuvants has the greatest impact on the environmental performances of earth construction, along with transportation (Anne Ventura et al., 2022). The advantages and disadvantages of adjuvantation are actually still under discussion in the scientific community (Marsh et al., 2020; Van Damme and Houben, 2020, 2018). In terms of technical effects, a recent study has shown that under 4 % of mineral binder admixture (which is considered as the maximum before increasing significantly the environmental impact of the earth material), the mechanical properties are not changed, only the resistance to water is increased (potentially useful to tackle erosion issue) (Ouedraogo, 2020). The usefulness of adjuvantation is therefore still under debate and should be thought about on a case-by-case basis.

4.4.2. 3D printing

Recently, different laboratories have investigated the possibility of 3D printing earth housings leading to different publications (M. Gomaa et al., 2022; Perrot et al., 2018). While such technique might be interesting in some specific contexts, its usefulness can still be questioned. Debates exist among professionals. Where some consider that 3D printing could reduce costs of earth construction, other are sceptical about the environmental and social impact of such technique.

4.5. Barriers to the development of earth construction?

From the beginning of this PhD journey, it has been noticed that many researchers use supposed barriers to the development of earth construction to introduce their research question, but without scientific references to support their assertions. By doing so, they build arguments to justify the relevance of their study.

Some of those barriers depicted are relative to technical issues and are used to justify technical research questions. For instance, the “high vulnerability to water erosion” (Cuccurullo et al., 2022); the high seismic vulnerability (Romanazzi et al., 2022; Sen and Saha, 2022); or the “difficulties of predicting behaviour” (Beckett et al., 2018; Champiré et al., 2016; Chauhan et al., 2022); are sometimes pointed out as barriers to the use of earth in construction. Pointing out technical issues to justify technical research question is not astonishing. However, it is not only technical hypothetical barriers that are pointed out, even if it still to justify technical research questions. For example, the “expensive, artisanal and complicated process” (Moevus et al., 2016); the lack of specific legislation (Giuffrida et al., 2021); the low productivity (Pinel et al., 2017); the time and labour constraints (Landrou et al., 2016); or the price and insurability difficulties (Perrot et al., 2018); are also barriers depicted in those articles introductions.

None of the above cited literature provide scientific references to justify the barriers pointed out, which represent a lack of rigour. However, one can ask if it is only a lack of rigour because some are not necessarily true and cannot be considered as such, except by trusting the authors of those articles, which is not acceptable in scientific research.

This reflection can raise one of the research questions of this thesis: are there and what are the barriers and drivers to the use of earth in construction? It also helps to introduce one of the main assumptions of this work: if (1) articles are introduced based on assumptions of supposed barriers to the use of earth in construction, helping to justify the research carried and (2) these assumptions rely on no scientific evidence then (3) besides lacking rigour, those assumptions might carry opinions (consciously or not) of the researchers that wrote those articles, which highlight a lack of objectivity and situating (i.e. consciously situated knowledges). Therefore, (4) situated knowledges could help to adopt a reflection on such assumptions and is useful to not fall into this bias.

5. Thesis structure

Whether the research questions of the thesis or the aims and objectives, it can be categorized into two parallel levels of reflections: One from an epistemological perspective, let’s say external to the earth construction field; one internal to the field, related to research problem into the earth construction field. This section aims at defining these research questions, the aim and objectives related, the research methods chosen and finally the thesis outline.

5.1. Research questions

In that sense, and from the introduction provided above, two types of interconnected research questions are raised:

Table 0.1: Research questions of the thesis

From an epistemological perspective	*RQ1*	*1) What are the biases related to non-situated knowledge in the earth construction field?* *2) What could be situated research in the earth construction field?*
Internal to the field	RQ2	1) How to assess compressive strength for small, rammed earth specimens in laboratories representative to the on-site? 2) Are there and what are the barriers and drivers to the use of earth in construction? 3) How to study barriers and drivers to the use of earth in construction?

The two epistemological research questions (RQ1.1 and RQ1.2) are related to the aim of the thesis presented in section 3.3. The research question RQ2.1 corresponds to the civil engineering study that have been done at the start of the PhD journey. Finally, the two research questions RQ2.2 and RQ2.3 were introduced in section 4.5. These RQ are interconnected. Indeed, as introduced in section 1, the epistemological reflections in this thesis raised initially from the investigation of the RQ "internal to the field". However, as a matter of clarity, the research questions, aims and objectives related to the epistemological issues will be written in italic in this section.

5.2. Aim and objectives

To describe conceptually the aim and objectives, the metaphor of the principle of vision used by Donna Haraway can be used. Three problems (A problem, here, is constituted of objective and research question associated) are investigated in this thesis φ_1, φ_2, and φ_3 (Table 0.2). These problems will be observed with the vision of the researcher who is part of the socio-political realities[52] and therefore carrying its own values and potential bias. The researcher observes these problems through the lenses of the research methods adopted, aiming to translate part of the realities into knowledge. In our case, observing different, although interconnected problems, will help to situate this knowledge translated, meaning, in particular, to identify better the limits of the observation (Figure 0.20). In that context, the section 2.2 and the declaration of values had the objective of being as transparent as possible (i.e situating) about my situated researcher's vision.

[52] Here again, the plural is privileged to distinguish with positivism view where there is a single reality observable from the outside.

Table 0.2: Problems and related objectives of the thesis

Problem	Objective	Research question addressed
φ_1	1. Propose a similitude relation to manufacture rammed earth specimens in laboratories representative to the on-site.	How to assess compressive strength for small, rammed earth specimen in laboratories representative to the on-site?
φ_2	2. Identify what the literature says about barriers and drivers to the use of earth in construction. *3. Identify potential bias associated with non-situated research.*	Are there and what are the barriers and drivers to the use of earth in construction? *What are the biases related to non-situated knowledge in earth construction field?*
φ_3	4. Identify obstacles and drivers encountered in a showcase rammed earth building project. *5. Describe the performance approach adopted in the building project allowing to situate the first problem* φ_1	Are there and what are the barriers and drivers to the use of earth in construction? How to study barriers and drivers to the use of earth in construction? *What could be a situated research in earth construction field?*

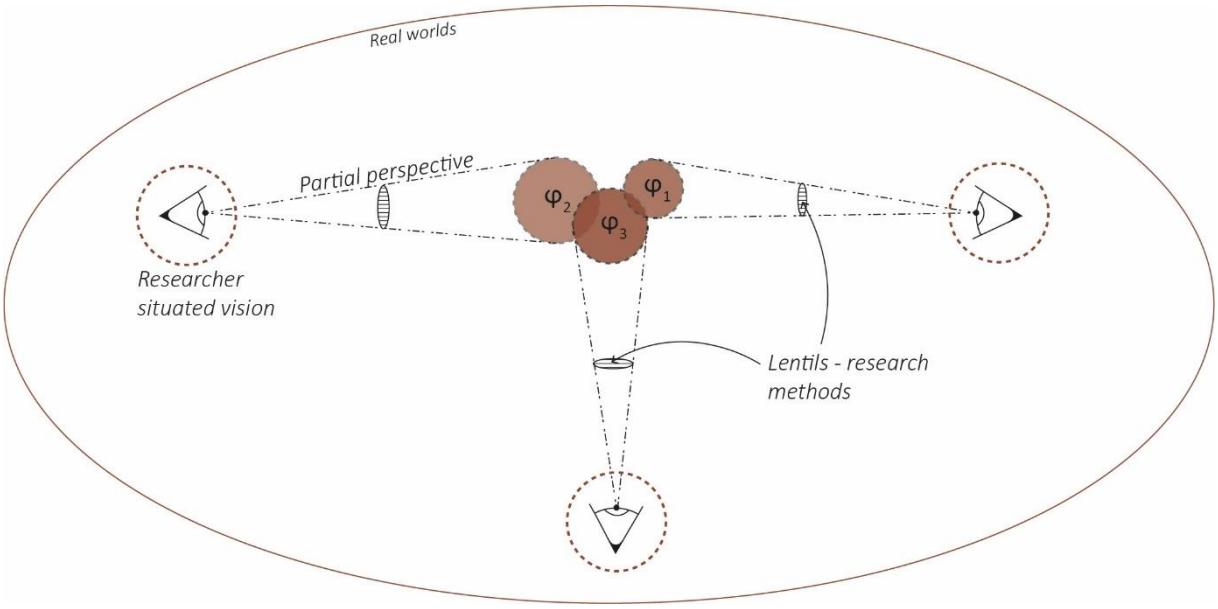

Figure 0.20: Conceptual representation of the study considering the concept of situated knowledge of Donna Haraway

As the aim is to propose a reflection on what could be a situated civil engineering research, the first problem φ_1 is a typical mechanical engineering problem that can be described under this research question:

> *How to assess compressive strength for small, rammed earth, specimens in laboratories representative to the on-site bigger elements (like walls)?*

Then, the other problems observed will aim at achieving two goals: gaining reflexivity about the first problem φ_1 in a situated knowledge approach (i.e. aiming at situating this problem in socio-political realities), and answering the second research question (RQ2) described above. We will see that observing these issues will also help to offer insights into RQ1.1 described in the previous section. These problems are at different scale than the problem φ_1. Indeed, φ_2 focus on a field scale of earth construction, while φ_3 is dedicated to construction project's scale. The different objectives associated are depicted in Table 0.2.

It is essential to note that, while the problems φ_2 and φ_3 seem, at first glance, far from the first problem, they were necessary to adopt a reflexivity approach to situate, at least partially, the problem φ_1 in the socio-political realities.

5.3. Research methods: a pluridisciplinar research

A pluridisciplinar approach have been chosen for this thesis. Firstly, this was based on my background being pluridiscplinar (double master in civil engineering and architecture). Then, being at the interval between different discplines allowed to adopt a reflexive posture consistent with the situated

knowledges theory (see section 3.2). These discplines could be defined as civil engineering (problem φ_1) and architecture (problem φ_2 and φ_3). Relying on different disciplines mean using different research methods (Figure 0.21): literature review; laboratory work analysis; and case study analysis through interviews and document analysis. Therefore, these methods combine quantitative analysis (laboratory work addressing the objective 1), but also qualitative analysis (literature review addressing the objective 2, and objective 3; and case study analysis addressing the objective 4 and 5). Hence, this thesis can be considered as a mixed-method approach as defined by (Creswell, 2013).

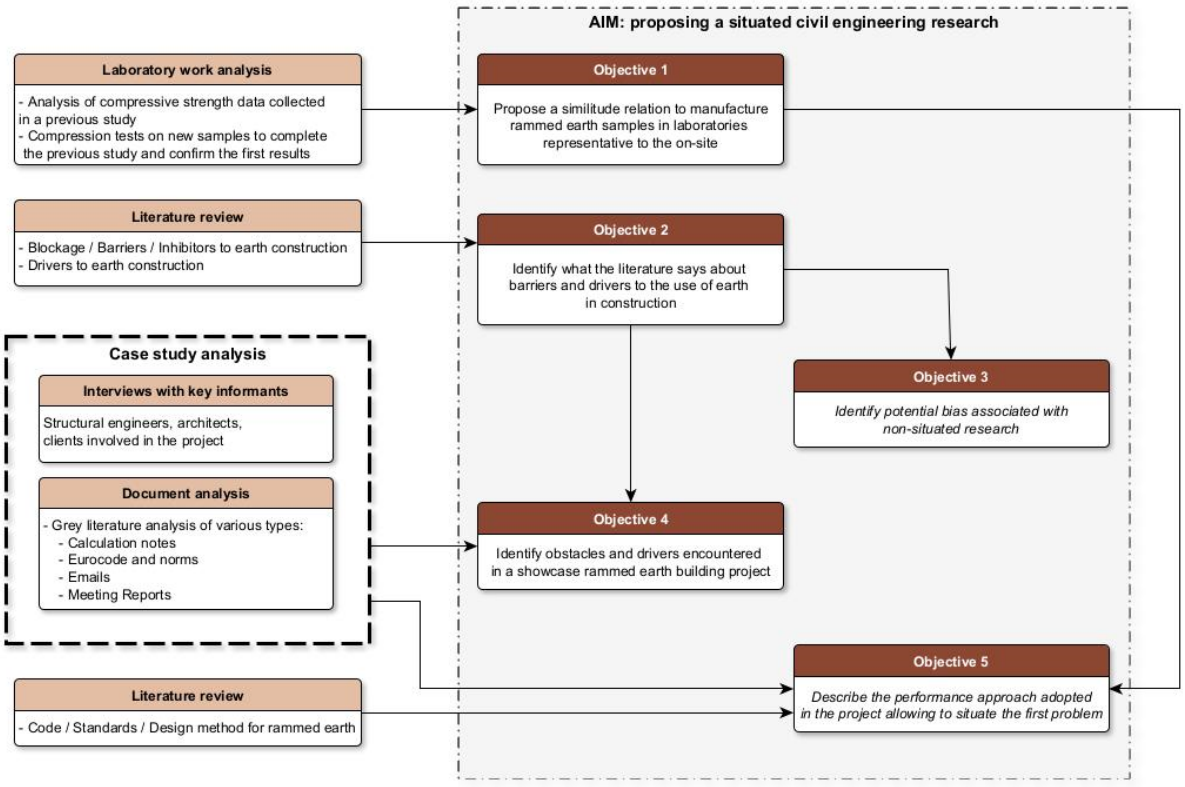

Figure 0.21: Scheme representing the research methods employed to address the different objectives of the thesis

5.4. Thesis outline

This thesis is split into six chapters (Figure 0.22). It was decided to put the chapter dealing with objective 1 first. Indeed, the approach of this thesis, in accordance with *situated knowledges* theory, is reflexive. Thus, while the objective 1 addressed is, strictly speaking, a question of civil engineering, the other objectives aimed to decentre the vision by keeping in mind to situate the method developed in Chapter 1. Decentre the vision is necessary to understand that the research is intrinsically situated. That is why, it has been decided to keep objective 1 to start the thesis and conclude it with chapter 6. The latter, indeed, aim to situate the method of chapter 1, while chapters 2 to 5 will decentre the vision. Therefore:

Chapter 1 develops a similitude relation helping to manufacture rammed earth specimens in laboratories with greater representativity of the on-site, in terms of compressive strength. In particular, it highlights that sieving an earth to obtain results with low variability of compressive strength, implies considering equivalent parameters of dry density and water content, to adjust in comparison with the on-site. A journal peer-reviewed article has been published from this work. In this article, we (with the co-authors) had already some intentions to situate the knowledge produced for this study. Indeed, this knowledge was introduced from the case study. However, at that time we were not aware of the situated knowledges theory and not conscious of the potential bias that can carry articles introduction, in particular through using "barriers" and "drivers" without any scientific evidence. Therefore, first to discuss this potential bias, it was useful to establish a literature review of the articles addressing barriers and drivers to the use of earth in construction.

Chapter 2 is an extensive literature review addressing the following issue "*Are there and what are the barriers to the use of earth in construction?".* Different factors (barriers or drivers) influencing the use of earth in construction have been identified and classified into five categories, although interconnected: technical, economic, political, organizational and socio-cultural. Highlighting a lack of contextualisation and situation of some researches on barriers and drivers, a conceptual framework for investigating barriers and drivers is proposed in this chapter and will be applied in subsequent chapters. Finally, this chapter helps to make visible the bias that many technical studies have when introducing their technical research questions using *barriers* or *drivers*.

Chapter 3 describes the methodology employed for the next chapters of this thesis: a single buildings' case study analysis. The methodology is inspired by science and technology studies to define what is the scope of the study: not only the finished building will be considered but also the design process, involving various stakeholders, the whole being part of a socio-technical system. So, technical problems will be discussed along with political, economic, organisational and socio-cultural ones. The analysis of the building's case study is grounded on document and email analysis combined with an interview campaign with various stakeholders involved in the building's design process. The study is situated in the time between the winning of the competition and the delivery of the building.

Chapter 4 aims at situating the barriers and drivers' study (chapter 5 and 6) to adapt the conceptual framework (developed in Chapter 2) into the case study analysis. By doing so, a definition of *barriers* and *drivers* is provided. Firstly, the specificities of the French normative system are highlighted, as the lack of standards has been identified in the literature as a potentially important barrier, which allowed us to understand the central role of control officers. Then, some specificities of the building project are also described including, in particular, the fact that it was part of an urban project and an overall

project of five buildings, as this was seen as a facilitating factor for the use of earth in the building studied. Common and uncommon stakeholders, involved in the case study, are introduced. Finally, the evolution of technical choices related to the earth in the project is described, bringing to light that the result (being load-bearing rammed earth facades) was not initially planned but instead was the result of a process. For the next chapters: barriers and drivers to the use of earth in that specific building should be understood as all the challenges faced by the stakeholders to achieve a consensus on the technical solution of load-bearing rammed earth facades, considering the specific context of this building project.

Chapter 5 points out different challenges that have been identified in the design process of the building through the description of the evolution of different technical elements, including the questioning of the load-bearing capacity of the wall and the definition of the wall itself. Different technical elements are taken as examples to understand how a consensus was reached, in particular: the erosion management and the use or not of insulation. Finally, insights are provided on the collaborative work and challenges associated.

Finally, chapter 6 describes the different key steps of the performance design approach adopted for the building: resource selection, characterization and quality control, in which compressive strength played a crucial role (objective 5). These key steps can be seen as drivers as they helped for the acceptance of the load-bearing rammed earth façades (objective 4). This chapter is first introduced by situating this approach and by highlighting some political implications related to it. However, it is not a question of analysing these political implications, but only of highlighting them for the sake of transparency and reflexivity in order to situate the method proposed in Chapter 1 in socio-political realities. Therefore, this chapter ends with reflections on situated knowledges theory for civil

engineering research, in particular by proposing an autocritique of the introduction of the article published from the knowledge developed in Chapter 1.

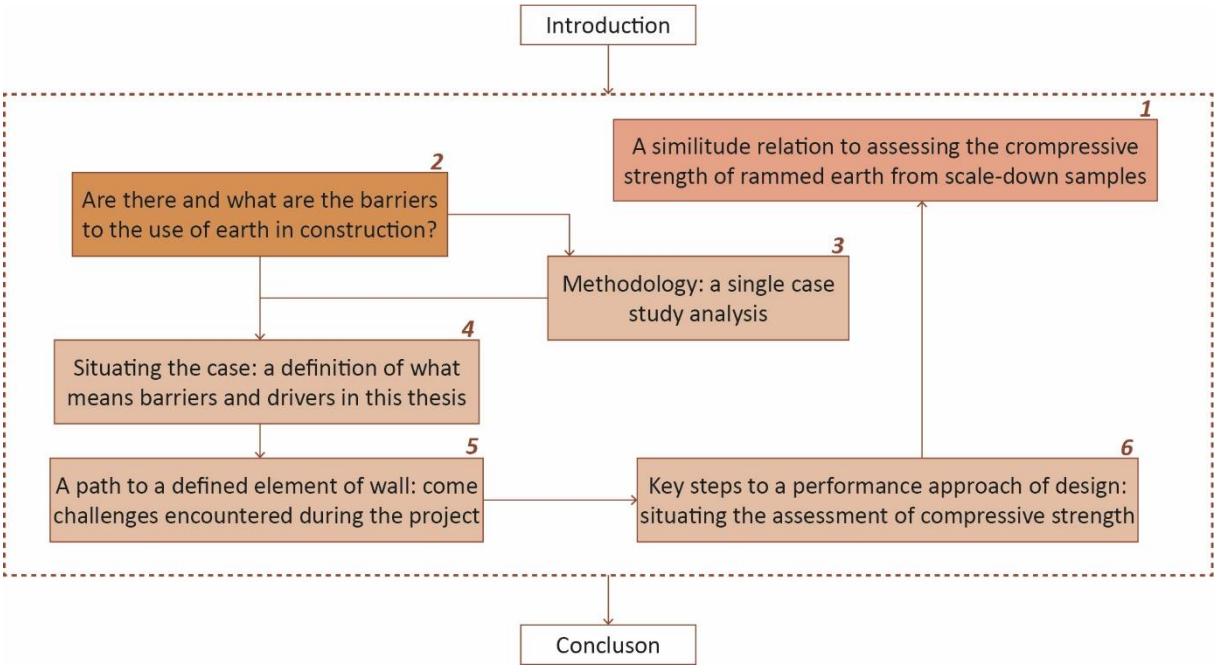

Figure 0.22: Thesis outline. The number above each box represents the chapter number. The different colours correspond to different methodologies. The arrows indicate the relation between the different chapters

1 *A similitude relation to assessing the compressive strength of rammed earth from scale-down specimens*

This chapter develops a similitude relation helping to manufacture rammed earth specimens in laboratories with greater representativity of the on-site, in terms of compressive strength (objective 1 of this thesis). In particular, it highlights that sieving an earth to obtain results with low variability of compressive strength, implies considering equivalent parameters of dry density and water content, to adjust in comparison with the on-site. It addresses objective 1 of this thesis which represents the knowledge than then will be situated thanks to Chapter 2 to 6.

1. Introduction

In some cases, for the design of building projects (in particular when there is a will to optimize the thickness of the walls), it can be useful to assess the compressive strength[53] (CS) of the material that will be used. Indeed, in the case of earth material, some authors (Dick and Krahn, 2015; Giuffrida et al., 2019; Walker et al., 2005), as well as standards (e.g. (New Zealand Standard (NZS), 1998)), recommend the application of compression tests before the execution of RE buildings or during the execution for quality control (Canivell et al., 2020). Currently, there is no standard testing procedure of compressive strength for rammed earth. The current RILEM[54] technical committee "274-TCE: Testing and characterization of earth-based building materials and elements" is responding to the need for new standardized test procedures, through round-robin tests, which would allow to compare results between different laboratories. This underlines the interest to study rammed earth compressive strength testing procedures.

Then, on one hand, rammed earth walls are generally (and traditionally) thick walls of about 500 mm, and on the other hand, it is easier to assess compressive strength on small specimens in laboratories (easier to manufacture, to transport, to dry, require smaller machinery, etc…). Therefore, the representativity of such tests can be questioned. This raises the research question that will be addressed in this chapter: how to assess compressive strength for small, rammed earth, specimens in laboratories representative to the on-site bigger elements (like walls)?

Different parameters influencing the CS already have been investigated. RE compressive strength is highly dependent on the water content, through the suction, which evolved considerably between the execution of the walls and the utilization of the building (Gerard et al., 2015; Jaquin et al., 2009). A relation between suction and CS, to predict the latter through Mohr-Coulomb criterium, has indeed already been proposed (Beckett et al., 2018). Additionally, the dry density of the material, linked to the energy of compaction and the manufacturing water content, is an important parameter as it has been shown that the higher it is, the higher the CS, for the case of CEB (Morel et al., 2007). The influence of the clay on the mechanical properties of rammed earth also has been explored. First, Hall and Djerbib (2004) found an increase in compressive strength when the amount of fine part (composed of clay and silt) increase from 20 to 30%, and a decrease in compressive strength when the amount is up to 40% (Hall and Djerbib, 2004). Then, the activity of these clays also has an influence on the mechanical properties, although further studies should be carried out to quantify it (Champiré et al.,

[53] The compressive strength refers to the ability of a material or structure to endure loads that tends to decrease its size.
[54] International Union of Laboratories and Experts in Construction Materials, Systems and Structures; the acronym come from the name in French

2016). Finally, the effect of friction, according to the aspect ratio[55], has been studied (Venkatarama Reddy et al., 2017), where an aspect ratio of 2 is recommended.

Testing small specimens of rammed raises the practical issue of the minimum size of specimens to obtain homogeneous and representative results. Indeed, on one hand, RE is a heterogeneous material. Firstly, the process of manufacturing by compacted layers of earth makes the material heterogeneous with higher density on top of the layers than on the bottom (Q.-B. Bui et al., 2009a; Bui and Morel, 2009). Secondly, earth material is a natural heterogeneous material in itself as being composed of different grains of different sizes. In particular, RE is often composed of gravels, between 2 and 20 mm in diameter, and sometimes with stones of size higher than 50 mm (Gomes et al., 2014; Rojat et al., 2020). On the other hand, it would be costly and time-consuming (due to the drying process) to perform laboratory tests on wallettes or real-size specimens, which are representative of the site construction. Few authors have studied the scale effect[56]: Some, by testing two sizes of extruded earth bricks, have shown the possibility to obtain similar results between small and large-scale bricks (Maskell et al., 2013). While others, by testing various RE specimens sizes (cylinders, full-scale prisms, and full-scale columns) of the same material, have found significant lower results for Full-scale prisms than small cylinders (Maniatidis and Walker, 2008). The authors attributed this decrease to different reasons: variation in material grading, subsequent crushing of the higher aggregate content during compaction, and variation in compactive effort. Besides, they recommend further investigation, in particular when assessing materials for rammed earth construction composed of a large proportion of grains above 20 mm (Maniatidis and Walker, 2008). Then, the impacts of the scale effect and the representativeness of laboratory tests according to the size of the specimens require further investigation for RE, in particular when there is a heterogeneity of specimens due to big grains (higher than 20 mm of diameter). Therefore, this chapter will describe a study based on more than 66 compression tests on an earth used in a real project, exploring the scale effect, by proposing a similitude relation of the CS considering the key parameters that drive the representativeness of the results (water content, dry density and the granulometry).

The earth investigated for this study was used for an office building (Figure 1.23) which is the case study of this thesis (see Chapter 4, 5 and 6, for further insights on the building). Following the classification of the ISO 14688-1 standard, that earth was composed of 8% of Clay (<2 µm), 11% of Silt (between 2 µm and 50 µm), 26% of sand (between 50 µm and 2 mm) and 55% of gravel (between 2 mm and 50 mm), Figure 1.24.

[55] The aspect ratio corresponds to the ratio between the height and width of the specimens.
[56] Potential influence of the scale of specimens on the results of compressive strength assessment.

On-site, the contractor sieved the earth at 50mm. They built a testing wall to assess the dry density and manufacturing water content of the RE implemented. Specimens of batches and the wall had been withdrawn and carried into the laboratory, the first to estimate the manufacturing water content by an oven-drying process, the second to obtain the dry density of the wall by hydrostatic weighing. The site-construction parameters obtained in the lab were a mean dry density of 1.90 g/cm3 with a standard deviation of 0.07 g/cm3 and a mean manufacturing water content of 8 % with a standard deviation of 1.1 %. These parameters are key parameters as it is known that the dry density has a high impact on the CS of earth materials (Morel et al., 2007) and the manufacturing water content influences the compactness of the material (Mesbah et al., 1999). They have been useful for the setup of the experimental campaign that now will be described.



Figure 1.23: Recent picture of the building (source: author)

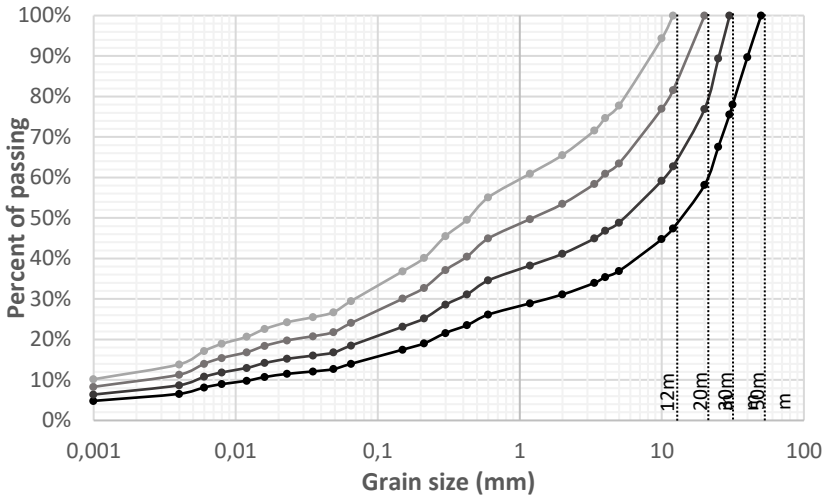

Figure 1.24: Grain size distribution. The same initial earth has been used but sieved at different maximum grain sizes (12, 20, 30 and 50mm). The darkest grey is the biggest the maximum grain size is considered, from light grey (12mm maximum grain size) to black (50mm maximum grain size).

2. Set up the experimental campaign

2.1. Specimens preparation

To design the similitude relation, nine full-scale prisms 300 mmx300 mmx600 mm, called full-scale (FS) prisms (FS_{20} and FS_{50}), made by the contractor, were used as a reference. The FS prisms labelled FS_{50} were manufactured with the same earth (same granulometry) as the earth used in situ for the building, while the earth was sieved at 20 mm for the FS_{20} prisms. Small specimens were then prepared, some by the contractor, and some in the laboratory. Two different geometries were studied: cylinders Ø160 mmx320 mm and prisms 160 mmx160 mm of section and 320 mm of height. The specimens, made by the contractor, were manufactured with a pneumatic rammer, while those made in the laboratory were made with manual rammers with a circular section for the cylinders and a square section for the prisms. For the cylinders, metallic moulds were used while for the small-scale prisms wood formworks were employed.

The aspect ratio was constantly equal to 2, as recommended by Venkatarama Reddy et al. (2007), who have shown for cement-adjuvanted RE that aspect ratios from 2 to 5 don't affect the results, while aspect ratios less than 2 tend to overestimate the results, because of friction between the specimens and the machine platen (Venkatarama Reddy et al., 2017).

To estimate the homogeneity of these specimens, the French standard on the testing procedure in compression for rock specimens (NF P 94-420, 2000) was taken as a reference. Although RE could be considered as soft rock, we used only the principle of homogeneity of the specimen that is linked to the continuum mechanics assumption and would not deeply vary with different geomaterials. The norm notifies that the biggest grain size of the geomaterial used to make the specimens should not

exceed 1/10 times the smallest length of the specimen (i.e. $d_{max}/Ø = 1/10$, where Ø is the diameter of the specimen and d_{max} the biggest grain size of the material). Following this size ratio is supposed to ensure the homogeneity of the specimen. For the small specimens, the size of the biggest grain should then not exceed 16mm (The diameters of cylinders are equal to 160 mm while the smallest length of the prisms is 160mm) while for the big specimens it should not exceed 30 mm. For earth, it has been shown by Seif El Dine that size ratios of 1/5 to 1/6 can be taken for triaxial compression testing (Seif El Dine, 2007). Therefore, to investigate the influence of the grain size fraction and the size ratio on the results, the earth was sieved at different maximum grain sizes: 12 mm, 20 mm, 30 mm and 50 mm. Table 1.3 summarizes the specimens manufactured for the study.

The small specimens (C_{50}) made with the same earth grading as on the building site (50mm-sieved earth) were manufactured with a targeted dry density of 1.90 g/cm^3 and a manufacturing water content of 8 % (corresponding to the on-site key parameters). The results obtained for those specimens were used as a matter of comparison with the ones for which the similitude relation was applied.

Table 1.3: Specimens manufactured, P prisms, C cylinders, FS Full-scale prisms, D Dimension, GSF Grain Size Fraction, M made by the contractor and L made in the laboratory, MPS Mass Proportion Sieved compared with the reference grading 0/50 mm or percentage of mass withdrawn.

Geometry	Prisms	Cylinders				Full-scale prisms	
D (mmxmmxmm)	160x160x320	Ø160x320				300x300x600	
Code	P_{12}	C_{12}	C_{20}	C_{30}	C_{50}	FS_{20}	FS_{50}
Number of specimens	6	8	21	4	18	2	7
GSF (mm)	0/12	0/12	0/20	0/30	0/50	0/20	0/50
MPS (%)	25%	25%	15%	5%	0%	15%	0%
Size ratio $d_{max}/Ø$	1/13	1/13	1/8	1/5	1/3	1/15	1/6
M or L	L	L	M	M	M	M	M

2.2. Similitude relation principle

For sieved earth, two options are possible. One is to use the same manufacturing water content and dry density as the earth implemented on-site with a grain size up to 50 mm. This option was chosen for the specimens sieved at 20 mm (C_{20}). However, in practice, this option leads to a too dry material that is quite complicated to compact at the targeted density. Indeed, the water is mainly contained in the fine portion of the earth that is the clay-silt-sand-matrix, simply called here the clay-matrix. So, while removing big grains by sieving, with the same manufacturing water content, there will be less water in the clay-matrix, in proportion, than in un-sieved earth.

Therefore, under the premise that the cohesion of the material is mainly due to the clay-matrix, one other option, which is chosen here, is to ensure the same manufacturing water content and dry density of the clay-matrix of the specimens, whatever its grain size proportion. In other terms, it is necessary to calculate the manufacturing water content and the dry density that should have the specimens' clay-matrix at X (where X=12 mm, 20 mm or 30 mm here) to reach the same clay-matrix dry density and manufacturing water content as the 0/50 mm reference earth (Figure 1.25).

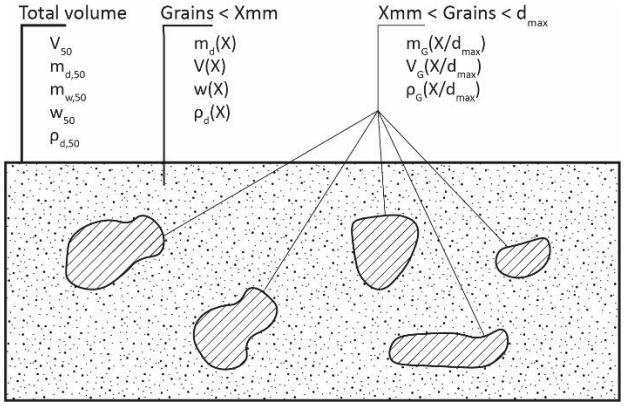

Figure 1.25 : Schematic illustration of an earth

By definition, the mass proportion of material with grain size lower than X within a volume of 0/50mm earth, denoted by $P(X)$, is equal to:

$$P(X) = \frac{m_d(X)}{m_{d,50}} \tag{1}$$

Where $m_{d,50}$ is the dry mass of the 0/50mm material and $m_d(X)$ is the dry mass of the grains of size lower than X. The dry density of these grains within the volume V_{50} of 0/50mm material is equal to:

$$\rho_d(X) = \frac{m_d(X)}{V(X)} \tag{2}$$

Where $V(X)$ is the volume of grains of size lower than X within the volume V_{50} of 0/50mm earth. $V(X)$ cannot be directly measured. Similarly, the solid density of the grains of size higher than X within the volume V_{50}, which is denoted by $\rho_G(X/d_{max})$, writes in the form:

$$\rho_G(X/d_{max}) = \frac{m_G(X/d_{max})}{V_G(X/d_{max})} \tag{3}$$

Where

$$m_G(X/d_{max}) = m_{d,50} - m_d(X) \text{ and } V_G(X/d_{max}) = V_{50} - V(X) \tag{4}$$

Again, $V_G(X/d_{max})$, which is the volume of grains higher than X contained in the volume V_{50}, cannot be measured. $\rho_G(X/d_{max})$ was measured through hydrostatic weighing of grains of different grain size

higher than 12 mm, then the mean value was obtained and $\rho_G(X/d_{max})$ was taken constant equal to 2.35 g/cm^3.

Then,

$$\rho_d(X) = \frac{m_d(X)}{V(X)} = \frac{P(X).m_{d,50}}{V(X)} = \frac{P(X).m_{d,50}}{V_{50} - V_G(X/d_{max})} = \frac{P(X)}{\frac{V_{50}}{m_{d,50}} - \frac{V_G(X/d_{max})}{m_{d,50}}} = \frac{P(X)}{\frac{1}{\rho_{d,50}} - \frac{V_G(X/d_{max})}{m_{d,50}}} \quad (5)$$

Whereas from (1) and (4):

$$m_{d,50} = \frac{m_G(X/d_{max})}{1 - P(X)} \quad (6)$$

Finally, from (5) and (6), the calculation of the dry density of the 0/X proportion contained in the 0/50mm reference earth, denoted by $\rho_d(X)$, can be made through the relation:

$$\rho_d(X) = \frac{P(X)}{\frac{1}{\rho_{d,50}} - \frac{1 - P(X)}{\rho_G(X/d_{\max})}} \quad (7)$$

where $P(X)$ is the mass proportion of material with grain size lower than X within a volume of 50 mm earth; $\rho_{d,50}$ is the dry density of the un-sieved material (equal to 1.90 g/cm^3) and $\rho_G(X/d_{\max})$ is the dry density of the grains higher than X within the volume V_{50}.

Similarly, for the same volume V, the water content of the 50 mm-sieved material is given by:

$$w_{50} = \frac{m_{w,50}}{m_{d,50}} \quad (8)$$

Where $m_{w,50}$ is the mass of water (kg) inside the volume V. It is assumed that this mass is equal to the mass of water inside the fine part as grains of size higher than X are non-porous[57] and the water at the interface grains/matrix is neglected[58], i.e. $m_{w,50} = m_w(X)$ for X = {12, 20, 30}, where $m_w(X)$ is the mass of water contained in a volume of 0/X mm earth (which was checked for X=12 mm through an immersion test).

Then, with equations (1) and (8), we obtain the water content within the 0/X proportion of the un-sieved material, which is denoted by $w(X)$:

$$w(X) = \frac{w_{50}}{P(X)} \quad (9)$$

[57] The non-porosity of the grains has been verified for the specific earth of this study. Indeed, the weigh of dry grains have been compared with the one of grains that have been submerged under water, finding a constant weigh.

[58] See appendix A1 for a justification of this hypothesis.

where w_{50} is the water content of the un-sieved material taken as a reference (equal to 8 %). Results of $\rho_d(X)$ and $w(X)$ obtained for *X*= 30 mm, 20 mm and 12 mm are reported in Table 1.4.

Dry density and water content effectively used for the fabrication of specimens made with the earth of maximum grain size equal to *X* are, on their side, denoted by $\rho_{d,X}$ and w_X. The manufacturing water contents (w_X) were measured by oven-drying and weighing specimen of batches while fabricating the specimens. The specimens were weighed before drying and then put in the oven at 105°C and regularly weighed until a constant mass. The dry densities ($\rho_{d,X}$) were calculated by knowing the water content, the volume, and the mass of specimens.

For all the specimens, the condition $w_X = w(X)$ has been satisfied to within 0.2 % so that the manufacturing water content for the clay proportion of all the specimens can be considered to be the same. However, as it is shown in Table 1.4 and underlined at the beginning of this section, the condition $\rho_{d,X} = \rho_d(X)$ (to within 0.01 g/cm^3) is satisfied for X = 30 mm and 12 mm, while for the specimens made with the 0/20 mm earth the condition $\rho_{d,20}$=$\rho_{d,50}$ (to within 0.01 g/cm^3) was applied.

Table 1.4: Corresponding P(X) for different grading for the earth studied, their targeted manufacture parameters ρ(X) and w(X) calculated through equations (7) and (9), except for X=20 mm, for which ρ(X) is targeted equal to ρ_{d50}, and $\rho_{d,X}$ and w_X, respectively the dry density and the manufacturing water content actually measured after manufacturing.[59]

X	**50 mm**	**30 mm**	**20 mm**	**12 mm**
P(X) [%]	100	94	87	77
ρ_d(X) [g/cm^3]	1.90	1.88	1.85	1.80
$\rho_{d,X}$ [g/cm^3]	1.91	1.88	1.91	1.79
Standard deviation [g/cm^3]	0.05	-	0.04	-
w(X)= w_X [%]	8	8.5	9	10.5

The principle of the process to manufacture specimens following the similitude relation described above is presented in Figure 1.26.

[59] Some data are missing (standard deviation of dry densities of 30mm and 12mm earth specimen) as the manufacturing and testing were not performed by the candidate but by an internship student.

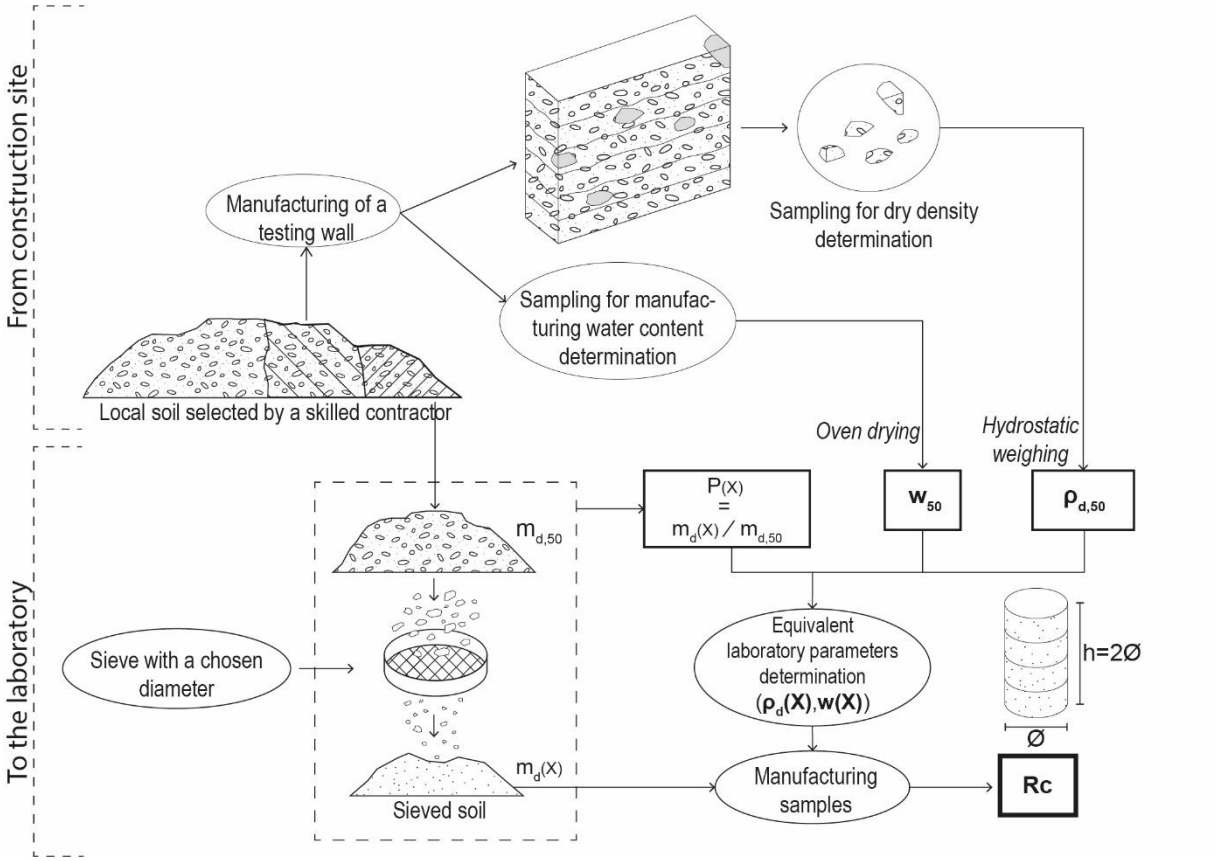

Figure 1.26: Scheme of the process to manufacture specimens with equivalent parameters, where ($\rho_{d,50}$,w_{50}) are the site construction key parameters, respectively dry density and manufacturing water content; P(X) is the percentage of passing obtained from the total dry mass of un-sieved earth $m_{d,50}$ and the dry mass of earth after sieving $m_{d,X}$; (ρ_d(X),w(X)) are the equivalent parameters obtained through the similitude relations, respectively dry density and manufacturing water content of sieved earth, Ø is the diameter of the specimen and h its height. (Source: authors)

2.3. Specimens conditioning

For each type and geometry of specimens, different curing conditions were performed to obtain different testing water content and thus the evolution of the compressive strength (CS) against the testing water content. Three states of specimens were tested: dry (about 1 %), intermediate water content (between 2 and 8 %) and wet (8 to 10 %). These states have been defined from the construction project. Indeed, the manufacturing water content on-site was around 8 % and during the life of the building, the water content inside the walls will not climb above this value except in exceptional cases (pathology), which are not considered here. The dry state of the water content of 1 % corresponds to the service phase of the building, at the end of the drying process of the wall. This value was obtained from a hygrothermal model in another study. And finally, the intermediate state is related to the drying process of the walls, which is thus contained between 8 and 1 %.

The specimens tested at a dry state were dried either in the oven at 50°C (to accelerate the drying process) or in the atmosphere of the laboratory until obtaining a steady mass through regular weighing. Whatever the drying process, before testing, specimens were hydrothermally stabilised in the atmosphere of the laboratory (temperature of 23°C +/- 3°C and relative humidity of 50 % +/- 10 %)

for a few days until the mass stabilised, for small-scale specimens, (160 mmx160 mmx320 mm prisms and Ø160 mmx320 mm cylinders) and several weeks until the mass has stabilised, for FS prisms (300 mmx300 mmx600 mm).

The ones tested at intermediate water content were either dried in the oven at 50°C or dried in the atmosphere of the laboratory. By knowing the manufacturing water content and the initial mass of these specimens, it was possible to estimate the mass corresponding to the targeted water contents. The specimens were regularly weighted and, when the targeted mass was reached, they were wrapped in an airtight plastic film until performing the compression tests. The water content homogeneity was assumed and verified after testing by measuring the water content selected from different places of the tested specimens. Specimens tested in a wet state were wrapped in an airtight plastic film directly after being manufactured and until being tested in compression. Whatever the curing condition, the specimens' top surfaces were coated with a thin layer of about 3 mm of clay-sand plaster which was applied at least 2 days before testing (only top surfaces because the ramming process led to perfectly flat bottom ones).

2.4. Experimental set-up

For the small-scale specimens (P_{12}, C_{12}, C_{20}, C_{30}, C_{50}), a hydraulic press was used with a force sensor of a capacity of 100 kN. For the FS prisms, (FS_{20} and FS_{50}) a hydraulic press was used with a force sensor of a capacity of 250kN. All the tests were controlled in displacement with a rate of 1.2 mm/min until the failure to obtain a rupture between 1 and 5 minutes as notified in the XP P13901 norm. Figure 1.27 presents pictures of the test settings.

Before each test, specimens were weighted and their size was measured. Latex layers were placed at the bottom and top of the small specimens to homogenise the stress transfer from the press to the specimens. After the failure, specimens were collected from the tested specimen to determine the water content by an oven-drying process at 105°C. Finally, by measuring the different sizes and calculating the volume, mass and water content of the specimens, their dry densities were calculated.

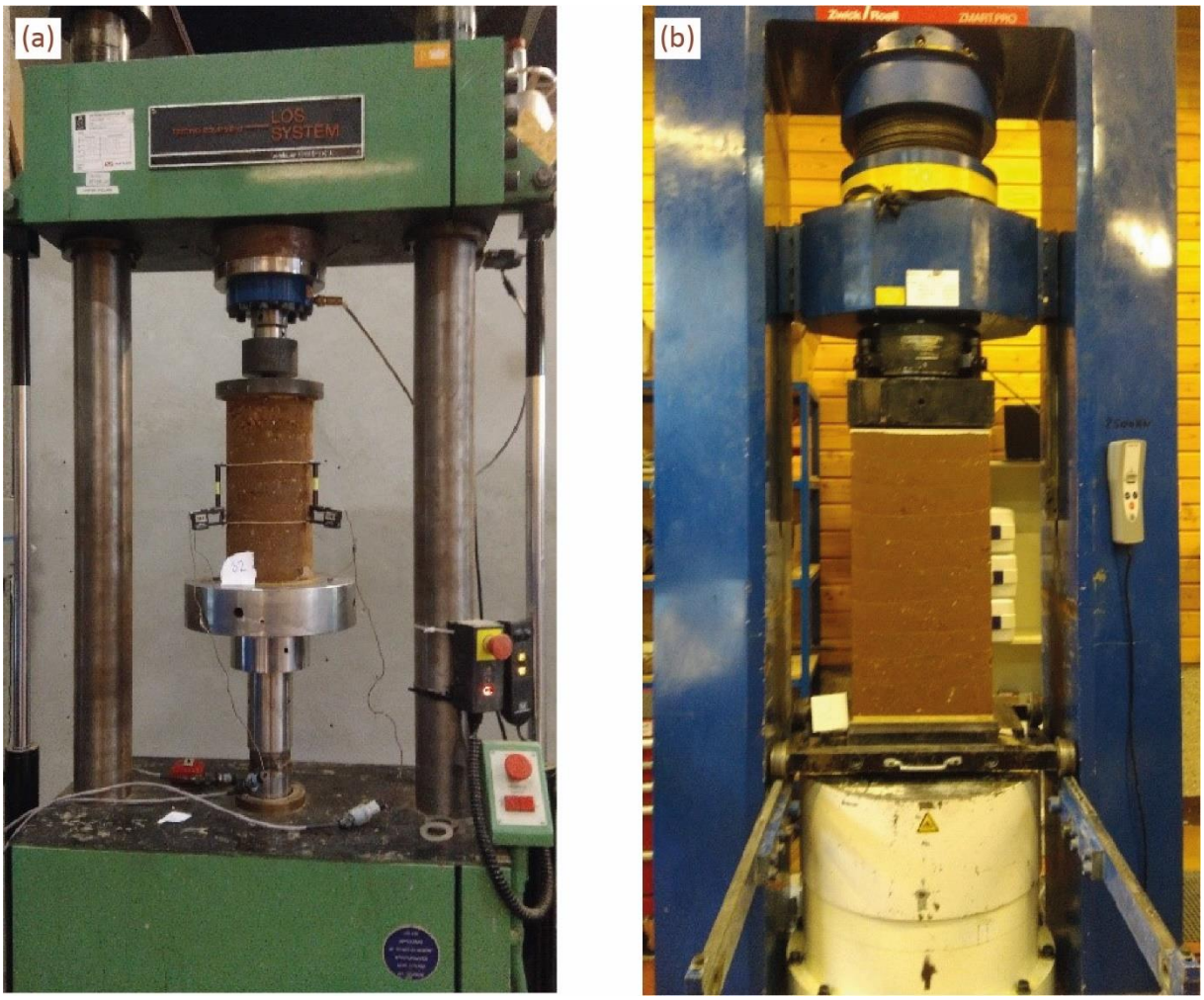

Figure 1.27: (a) Picture of a cylinder tested; (b) Picture a full-scale prism tested.

3. Results and discussion

3.1. Raw results

The results obtained (Figure 1.28) are consistent with previous literature. An increase in the CS while the water content decrease is noted (Bui et al., 2014a; Champiré et al., 2016). For wet specimens (around 7 to 12 % of water content), the CS is between 0.05 and 0.25 MPa, while for dry specimens (around 0.5 to 2 %), the CS is between 0.65 and 2 MPa. This is relevant to results generally obtained for RE, reported in previous studies (Miccoli et al., 2014).

Exponential regressions were chosen to describe all the curves as simple models with a good correlation, although another model may fit better.

At first sight, these data do not show good consistency between the different types of specimens. However, a deeper analysis can be pursued considering different parameters that could influence the CS: the geometry, the grain size fraction, the density, the size effect, and the different correction that could be applied.

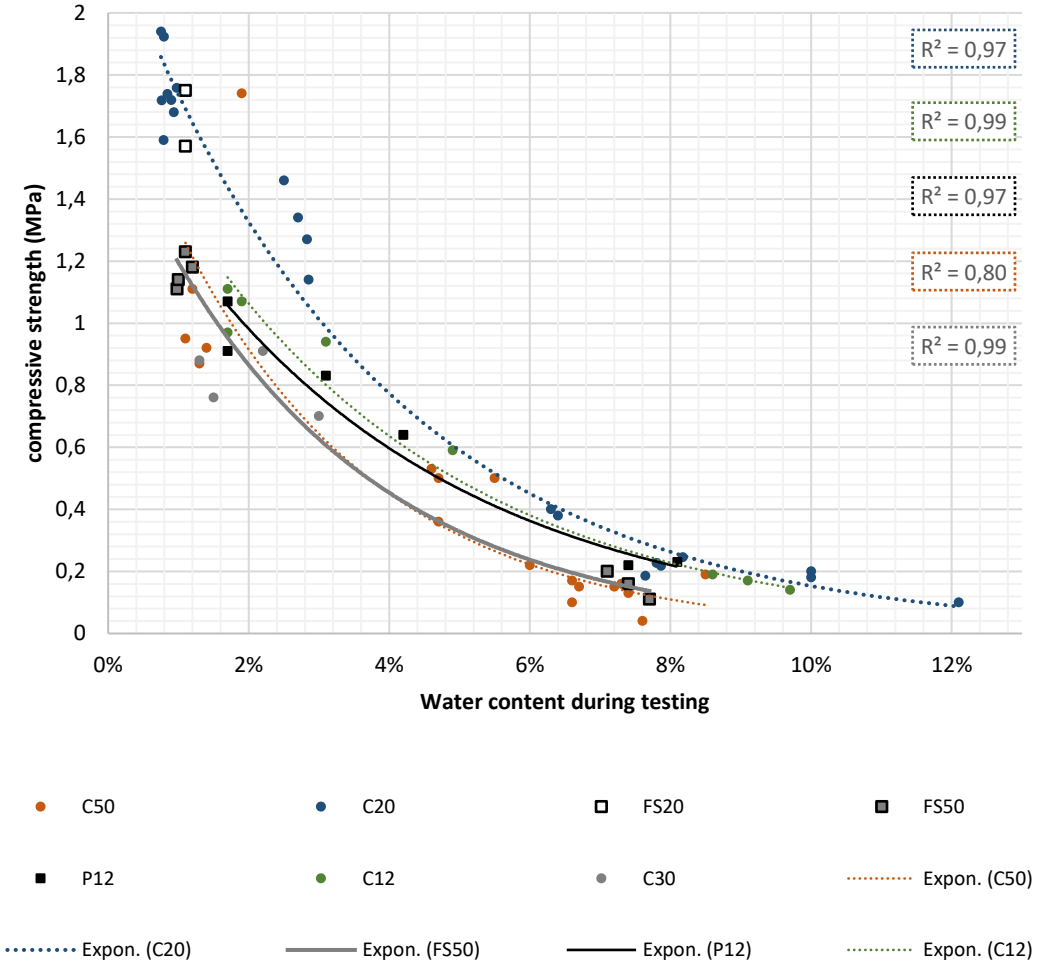

Figure 1.28: Compressive strength of all the specimens tested, against their testing water content

3.2. Influence of the geometry

The influence of the geometry of the specimens on the compressive strength was studied for those manufactured with 0/12 mm earth. For the latter, the size of the biggest grain is more than ten times lower than the size of the specimens whether they are cylindrical or prismatic (Table 1.3). These specimens can therefore be assumed homogeneous (NF P 94-420, 2000; Seif El Dine, 2007).

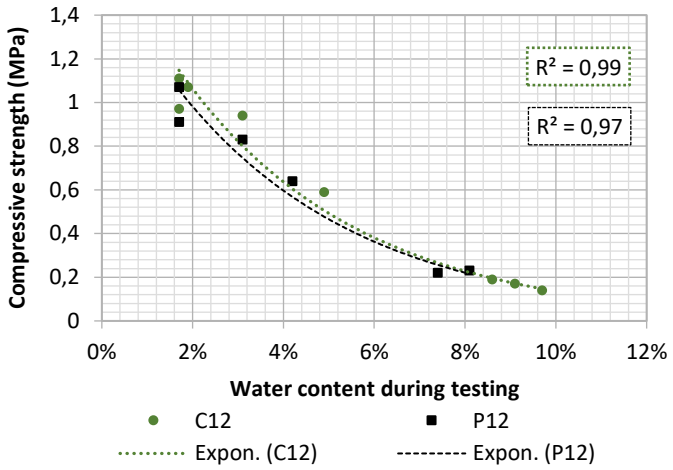

Figure 1.29: Compressive Strength against water content during testing for cylindrical (C12) and prismatic (P12) specimens.

The results obtained seem to indicate that the influence of the geometry is negligible (Figure 1.29), confirming what Venkatarama Reddy et al. (2017) obtained for cement-adjuvanted RE (Venkatarama Reddy et al., 2017). However, we can observe slightly lower results for the P_{12} compared with the C_{12} in dry states (between 1 and 2 % of water content). This might be explained by the manufacturing process. Indeed, it was identified during the study that cylinders were easier to manufacture. The corners of the prisms were particularly brittle due to the stress concentration and then tended to partially break, particularly when moving the specimens in a wet state, which could lead to untestable specimens. Moreover, there might be an edge effect that could induce a lower local dry density on the corners and thus, a lower compressive strength. Both geometries of specimens could then be used to determine the CS for further studies. However, as cylinders are easier to manipulate, this geometry is recommended.

3.3. Influence of the grain size fraction and validity of the method of equivalent parameters

The influence of the grain size fraction was first estimated by comparison between the CS results obtained with the specimens of 0/12, 0/30 and 0/50 mm earth at several water contents. Results are

presented in Figure 1.30a. In the case of 0/12 mm, to ease the reading of data and according to Figure 1.29, both cylinder and prism specimens, are captioned under the same label.

Results appear quite different from one type of specimen to another. The two curves are distinct due to the difference in earth grading between the specimens.

First, for 0/30 and 0/50 mm earth, the size ratio of 1 to 10 between the smallest length of the specimen and the maximum grains size is not fulfilled. That may explain why the results of these specimens appear to be more scattered (R^2=0.8 for 0/50 mm specimens versus R^2=0.98 for 0/12 mm specimens). The heterogeneity induced by the presence of big grains could also lead to singular points. Indeed, as observed in Figure 1.30a, one specimen made with 0/50mm earth reached a CS of 1.74 MPa for a testing water content of 1.9 %. However, a higher dry density could also partially explain this result (dry density of 2.03 g/cm^3 compared with a mean dry density of 1.91 g/cm^3 for the other specimens of the same category). The number of big grains in small specimens has a high impact on the dry density (as grains have a mean dry density of 2.35 g/cm^3 in our case) and on the water content. Thus, the larger the size fraction, the more likely there is to have heterogeneity. There are two types of possible heterogeneity, one inside the specimens themselves and one between the specimens (variability of dry density or water content and thus variability of the results). Both can be induced by the presence of big grains in the earth used.

Secondly, as it is mentioned previously, the cohesion of the material is mainly provided by the clays and adsorbed water. Therefore, the dependency of CS on the water content should be linked to the amount of water within the clay fraction of the material. To avoid this problem, instead of using the specimen water content directly (which is the mass of water per unit of the specimen dry mass), an equivalent is used instead, which considers the fact that the proportion of clay in the earth increases when it is sieved. Following the same approach as the one presented in section 2.2[60], this equivalent water content can be written in the form:

$$w_{cor} = P(X).w \tag{10}$$

Where $P(X)$ is the mass proportion of material with grain size lower than X within a volume of 0/50 mm earth, and w is the measured testing water content of the specimen. w_{cor} can be defined as the equivalent water content that should have a specimen made with 0/50 mm earth to reach the same

[60] Although the approach is similar, one should be aware that the equation of section 2.2 was established for manufacturing water content, while it is here for testing water content. It corresponds therefore to two distinct corrections applied.

water content of its clay proportion as the tested specimen at a water content equal to *w* and made with a 0/X mm earth.

CS results obtained with the cylinders of 0/12, 0/30 and 0/50 mm earth in the function of the equivalent water content are presented in Figure 1.30b. This graph underlines that considering the equivalent water content tends to significantly reduce the discrepancies between the specimens made with earth of different grain size fractions.

Finally, the sieving of the earth and the use of the method of equivalent parameters make it possible to respect the ratio of 1 to 10 between the biggest grain and the smallest length of the specimen. By doing so, greater repeatability can be observed for 0/12 mm earth specimens compared with 0/50 earth specimens (Figure 1.30 (a) and (b)).

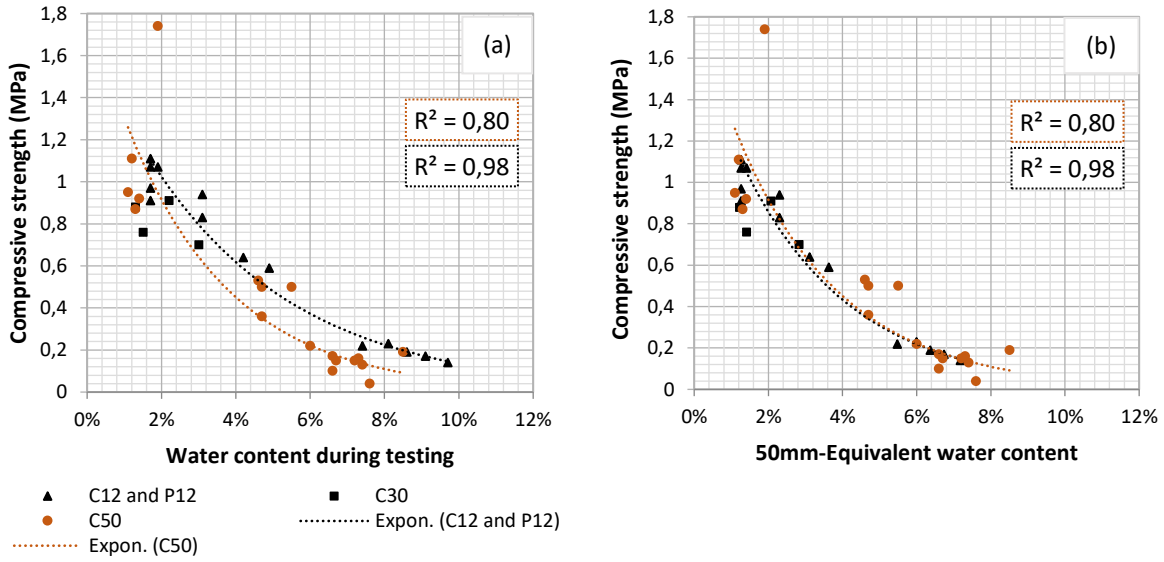

Figure 1.30: (a) CS against testing water content for C_{12}, P_{12}, C_{30} and C_{50}; (b) CS against 50mm-equivalent water content for C_{12}, P_{12}, C_{30} and C_{50}.

Note that the 0/20 mm specimens have been excluded from Figure 1.30 because their equivalent dry density is much higher (mean equivalent dry density of 1.97 against 1.90 for the other specimens). The next section 3.4 will then discuss the effect of density.

3.4. Effect of density

As noticed in Table 1.4, different dry densities were targeted to investigate the effect of the density. Figure 1.31 shows the results of 0/20 mm earth and 0/50 mm earth. These specimens were manufactured under the same conditions: similar mean dry density (1.91 g/cm^3 with a standard deviation of 0.05 g/cm^3 for C_{50} and 1.92 g/cm^3 with a standard deviation of 0.04 g/cm^3 for C_{20}), similar manufacturing water content (8 % for C_{50} and 9 % for C_{20}) and both manufactured by the contractor. Thus, Figure 1.31 shows directly the influence of the grading on the CS. Discrepancies can be observed

with significantly higher results for the 0/20 mm earth specimens. The two curves get closer when the corrected water content is considered (Figure 1.31b). However, the results still present a high variability between the two types of specimens. This illustrates the importance to account for an equivalent dry density as well. Indeed, a mean dry density of 1.92 g/cm^3 for the 0/20 mm earth specimens corresponds to a dry density of 1.97 g/cm^3 brought back to 0/50 mm earth, which can explain the gap between the two curves. Thus, targeting a dry density similar to that of the walls on-site and using sieved earth for manufacturing specimens might overestimate the actual CS.

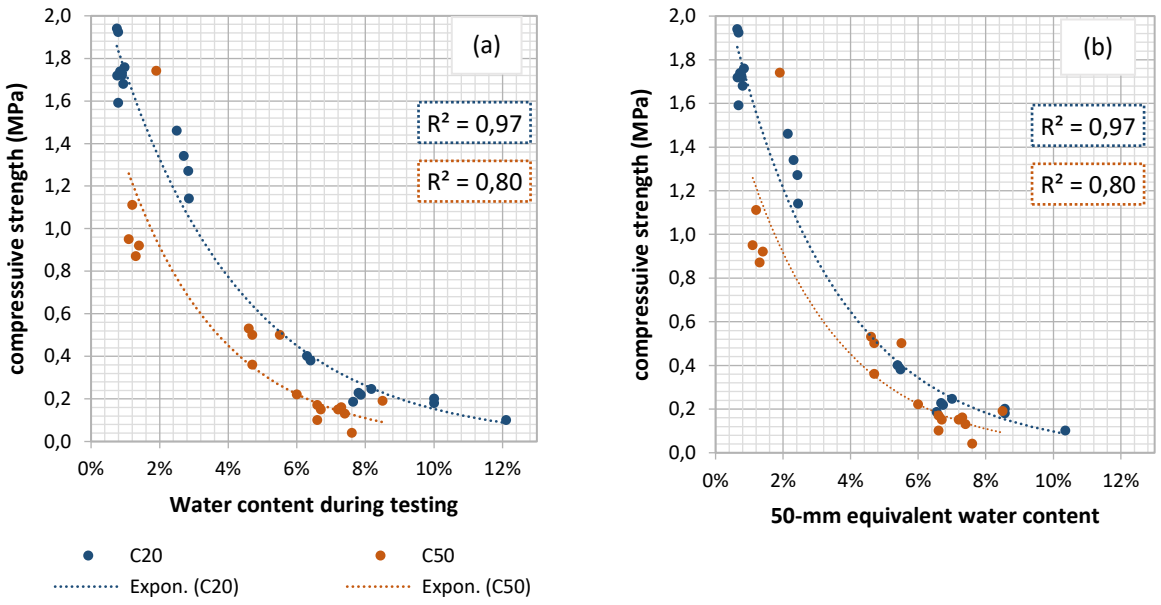

Figure 1.31: CS against testing water content (a) and 50 mm equivalent water content (b) of C_{20} and C_{50}.

To investigate the effect of density and apply a correction, the dry density of C_{20} specimens (considering here only those tested at a dry state) and the ones of FS_{20} were measured. The CS for those two types of specimens shows similar results (Figure 1.32). Indeed, for the mean water content of 0.8 % (standard deviation of 0.1 %) and a mean dry density of 1.93 (standard deviation of 0.10), we obtained for C_{20}, tested at a dry state, a mean CS of 1.76 MPa with a standard deviation of 0.10 MPa, while the mean CS obtained for FS_{20} is 1.66 MPa for a mean testing water content of 1.1 % and a mean dry density of 1.91. The C_{20} results are included in the margin of error of the W_{20} results. Moreover, the lower dry density, and the slightly higher water content of FS_{20}, compared with C_{20}, could explain the slight difference between these two results.

The size ratio for the specimens made with 0/20 mm earth is equal to 1/8, which is too high to follow the criteria of the norm on rocks (NF P 94-420, 2000). However, after testing, the earth of the specimens were sieved at 15 mm (corresponding to a size ratio of 1/10), and the grains between 15mm and 20mm in length represented only 5 % of the specimens. Thus, these grains can be assumed negligible. Therefore, following the norm, the specimens C_{20} were considered homogeneous.

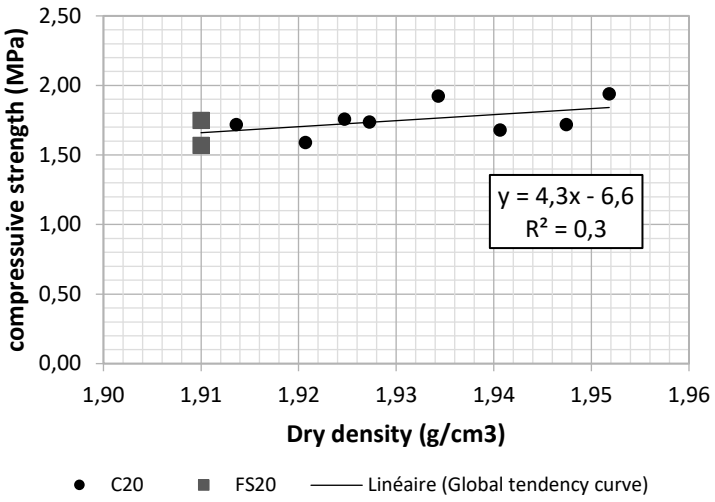

Figure 1.32: CS against the dry density of C_{20} and FS_{20} specimens with a mean testing water content of, respectively, 0.8 % (standard deviation of 0.1 %) and 1.1 %.

The results show that, under homogeneous conditions, it is possible to obtain representative results by testing small specimens.

While this output is limited because only two full-scale specimens were tested, it is promising for further consideration of the scale effect on RE specimens. It shows that with a ratio between the biggest grain and the smallest size of the specimens of 1/8 (for C_{20}, 20mm/160mm), we can obtain representative results compared with full-scale specimens (ratio of 20mm/300mm=1/15 for W_{20}).

To compare the results obtained on 0/20 mm earth specimens and those on C_{12}, P_{12}, C_{30} and C_{50}, a correction on the density is then required. Figure 1.32 shows the strength increases with an increase in dry density with a linear relationship. Because such a correlation has already been proved by different authors (Morel et al., 2007), this linear regression is used to estimate an equivalent CS for the C_{20} and FS_{20} specimens tested at a dry state. The C_{20} specimens have a mean dry density of 1.97 g/cm^3, thus, by targeting the dry density of the site construction at 1.90 g/cm^3, this corresponds to a decrease of 0.07 g/cm^3 and thus a decrease of 0.30 MPa applied to the eight specimens C_{20} tested at a dry state and the FS_{20}.

Figure 1.33 presents the results with this correction applied to the specimens tested at dry state (around 1% of water content). Fewer discrepancies are observed than in Figure 1.31b. This tends to validate our hypothesis of using equivalent parameters and particularly equivalent dry densities.

3.5. Comparison with full-scale specimens: scale effect

Finally, by applying all the corrections discussed in the previous sections 3.3 and 3.4, better-correlated results with a much lower variability can be obtained (Figure 1.33). In particular, fewer discrepancies,

than in Figure 1.28, can be observed between Full-scale prisms, representative of on-site construction, and small specimens. Slightly higher results are obtained for the dry specimens FS_{50} (300x300x600mm) compared with the small specimens (C_{12}, P_{12}, C_{30} and C_{50}). This could be due to a residual scale effect after the corrections. Then testing small specimens would tend to underestimate slightly the compressive strength, which goes in the direction of safety for building design. Further studies will be necessary, with other types of earth to investigate this.

In any case, the comparison of Figure 1.28 and Figure 1.33 shows the relevance to use equivalent parameters and the possibility to test small specimens instead of Full-scale specimens and still obtain representative results. This is an important outcome for further studies, as smaller specimens are much easier to manufacture and much cheaper to test in laboratories.

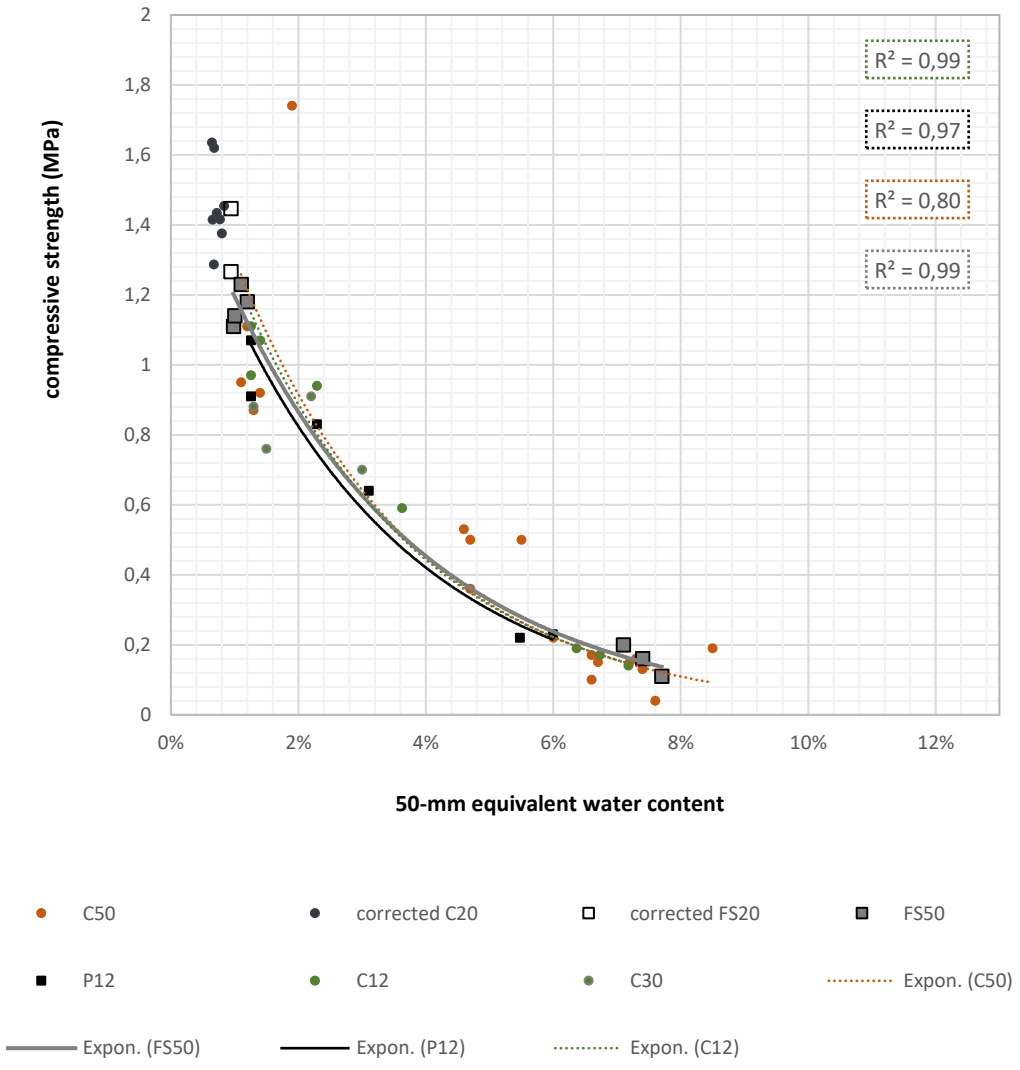

Figure 1.33: Results obtained of CS against equivalent testing water content after all corrections applied.

4. Conclusion

In conclusion, in this chapter were designed a similitude relation accounting for the sieving of earth material when it is required to manufacture homogenous small specimens representative to the on-site. A total of 57 small specimens have been compared with nine full-scale prisms. The analysis of the influence of different parameters on the compressive strength, such as the use of equivalent manufacturing parameters (dry density and manufacturing water content), the geometry, and the influence of the grading compared to the size of specimens highlighted the usefulness to consider equivalent key parameters (dry density and manufacturing water content). These parameters were first determined on-site and then the similitude relation was defined from these key parameters according to the sieving used for the different specimens. The specimens were then manufactured following the similitude relation. The principal outcomes of this chapter are:

- The geometry of specimens (cylinders or prisms) does not affect the compressive strength. This means that it is possible to obtain representative results of on-site walls by testing cylinders in the laboratory. It is recommended manufacturing cylinders instead of prisms because they have generally less default than prisms (stress concentration due to sharp edges). In any case, an aspect ratio of 2 should be chosen for the geometry of the specimens.
- For the same grain size fraction (0/20 mm), similar results can be obtained for two different sizes of specimens.
- The sieving of the earth for the preparation of specimens is useful for different reasons: to test smaller specimens (easier and cheaper), to obtain homogeneous specimens and then better results with fewer variations. Further studies could establish more precisely what ratio should be taken.
- The similitude relation is established with three equations to define equivalent parameters allowing us to reach similar results, whatever the sieving applied to the earth to make the specimens, between small-scale specimens and full-scale specimens.

Since this experimental study was done for one earth only and considering the high variability of earth for different sites, further studies could assess the validity of the similitude relation by investigating other earths. To do so, Appendix A2 can be followed. Moreover, the similitude relation proposed in that paper worked with an earth with a well-distributed grading. For example, with an earth with 5 % of clay (similar to the earth studied), but with no grains between 0 and 12 mm, specimens made with a fraction of 0/12 mm would have only been composed with clay which would probably have changed the compressive strength properties of the material.

Finally, the method proposed is based on assessed parameters from the on-site (dry density and manufacturing water content) and depend on the implementation made by the masons. Indeed, these parameters were assessed from specimens of a wall made by a mason. This raise the question of the interaction between the knowledge produced in this chapter and the socio-economic realities. For instance, if such approach was generalized, this might have influence on the role (positive or negative) of the masons in the design process. Therefore, as explained in the introduction of the thesis, I felt the necessity to situate this knowledge for two reasons: (1) Being involved in the building's project to which this research is related, I first became aware of the interactions with socio-political realities. Therefore, (2) I felt relatively responsible in potentially reshaping socio-economic realities for certain stakeholders in case such methods were to be widely adopted in the future.

In the related published article, while a tentative to situate this work has been achieved through the presentation of the case study, the embedment of the method proposed with the design approach of the building has not been fully described. As situated knowledges theory teaches us that any research is situated and researchers carrying these should be aware of it, then the next chapters aim to demonstrate and understand the situation of the knowledge corresponding to this chapter. This will allow us to establish an autocritique, particularly on the introduction of the article published it will be outlined that introductions often hide biases. In particular, as noticed in introduction of this thesis, researchers often justify their research question in introduction using hypothetical barriers, without scientific evidence. This highlight a will to situate their work, that is most of the time weak and made succinctly. Therefore, to investigate the main aim of this thesis, namely understanding what situated knowledges theory could bring to civil engineering research, the prism of investigating barriers to the use of earth in construction has been chosen. To do so, a literature review will be carried out in the next chapter on this topic.

2 *Are there barriers to the use of earth in construction today?*

This chapter is a literature review of the studies investigating the barriers and drivers to the use of earth in construction (objective 2 of this thesis). Through analysing the literature, barriers and drivers will be discussed and categorised under five categories (technical, economic, political, organizational and socio-cultural). Then, a gap in conceptualizing studies about barriers and drivers is identified and discussed, highlighting a bias related to a lack of situating such studies. A conceptual framework is therefore proposed for further studies on barriers and drivers. Finally, a discussion is made on studies using barriers to justify their research questions, pointing out a bias thanks to situated knowledges theory (Objective 3).

Part of this chapter is published as:
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1. Introduction

Despite the benefits of using earth in construction regarding the context of climate change and the environmental crisis context, a question arises: why are these construction techniques not more widely used in construction? Indeed, to illustrate, a study made a census in France of new earth construction between 1976 and 2015. The authors found a mean of 6.5 new earth buildings per year on that period. This can be compared to a mean of 79 195 000 m² of new construction per year on the same period (Antoine and Carnevale, 2016, p. 60). Therefore, an assumption could be that there are barriers to the use of earth as a construction material. This chapter will thus describe the literature addressing the following research questions: are there barriers to the use of earth in construction? What are these barriers? And what are the drivers?

The first part will be dedicated to explaining the method employed for the literature review. Subsequently, the documents selected will be presented and their quality outlined. Then, the factors affecting the use of earth in construction, identified in the selected literature, will be discussed. Based on the literature, a conceptual framework will be proposed to facilitate rigorous research on the topic of barriers and drivers to the use of earth in construction. Finally, through the lens of situated knowledge theory, a discussion will be made on scientific articles pointing out barriers, in introductions, to justify their research questions.

2. Methodology

The methodology used for the literature review is a systematic search and review. This section will describe the conceptual background of this method, the data collection and analysis process and finally the limits and validity of the method.

2.1. Conceptual background: a systematic search and review

Literature reviews provide an overview of a specific issue and help to identify gaps (Grant and Booth, 2009; Snyder, 2019). As it was assumed that only a few relevant pieces of literature would exist on the topic, a systematic search and review method was chosen (Grant and Booth, 2009). A systematic search and review method is a combination between a comprehensive search process and a critical review (Grant and Booth, 2009). This type of review combines the strengths of the methodology of a comprehensive search, for the data collection, with an in-depth analysis provided with a critical review (or integrative literature review) approach. Figure 2.34 summarizes the methodology applied for this chapter.

As the quality of a literature review depends on "*what literature is included and how it was selected*" (Snyder, 2019), the comprehensive search aims at minimizing bias in the selection of the literature. Indeed, a comprehensive search process intends to achieve exhaustive and comprehensive searching. This methodology is also applied to the selection of articles in systematic literature reviews (Grant and Booth, 2009). The latter aims at addressing a specific research question by performing a clear and transparent protocol and methodology for the selection of the literature. To prepare this protocol, the PRISMA-P (Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols) (Moher et al., 2015; Shamseer et al., 2015) has been used as guidance[61]. Hence, the search becomes repeatable and gains validity. This method has already been used in the construction field, for instance for components reuse (Rakhshan et al., 2020) or BIM[62] (Charef et al., 2018). Following the comprehensive search, the selected papers were split into 4 groups: Group 1 corresponds to articles identifying the factors (barriers or drivers) affecting the use of earth in construction by using a specific methodology; Group 2 is related to papers describing one type of barriers or drivers (for instance, related to regulation (Hurol et al., 2015)); Group 3 refers either to papers having only a subsection or notification addressing barriers and drivers, or papers referring to them but without specific methodology used to establish scientific evidence. Finally, while peer-reviewed journal articles were categorized into Groups 1 to 3, Group 4 corresponds to all the rest of the literature, including conference proceedings, master's thesis, reports and book chapters. Thesis identified through the selecting process were treated separately and further described in section 3.3 as it was necessary to position this thesis in comparison with previous work.

[61] PRISMA-P proposes a checklist of recommended items to address in a systematic review protocol. 10 items related to the methods to follow while conducting systematic review are proposed, including eligibility criteria, information sources, search strategy, or data collection process (Shamseer et al., 2015). Most of these items are covered in section 2.2.
[62] Building Information Modelling

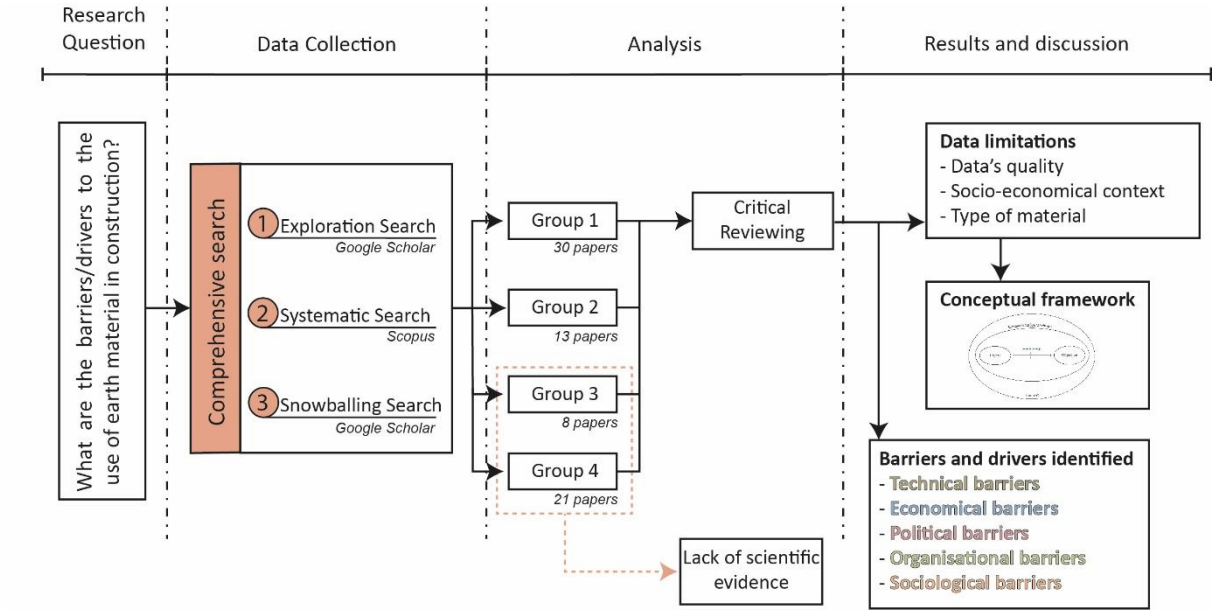


Figure 2.34: Scheme of the methodology to obtain the results presented in this chapter

Once selected and categorized, the papers were critically analyzed following the critical review principles. A critical review identifies both the strengths and the deficiencies of the literature (Torraco, 2005) and is usually used for either emerging topics, which is the case for barriers towards earth construction, or mature topics (Snyder, 2019).

2.2. Data collection and analytical method

The data collection process followed three main steps (Figure 2.35). First, the topic has been explored (step 1) to acquire knowledge and to build the keywords set (Table 2.5) for the second step. Secondly, a systematic search (step 2), based on the results of the first step has been performed to provide an exhaustive and repeatable literature review. Finally, a snowballing technique (both backward and forward) from the papers selected during the previous steps was used to validate the set of keywords and to crosscheck the two first steps, as well as to find potential grey literature (step 3).

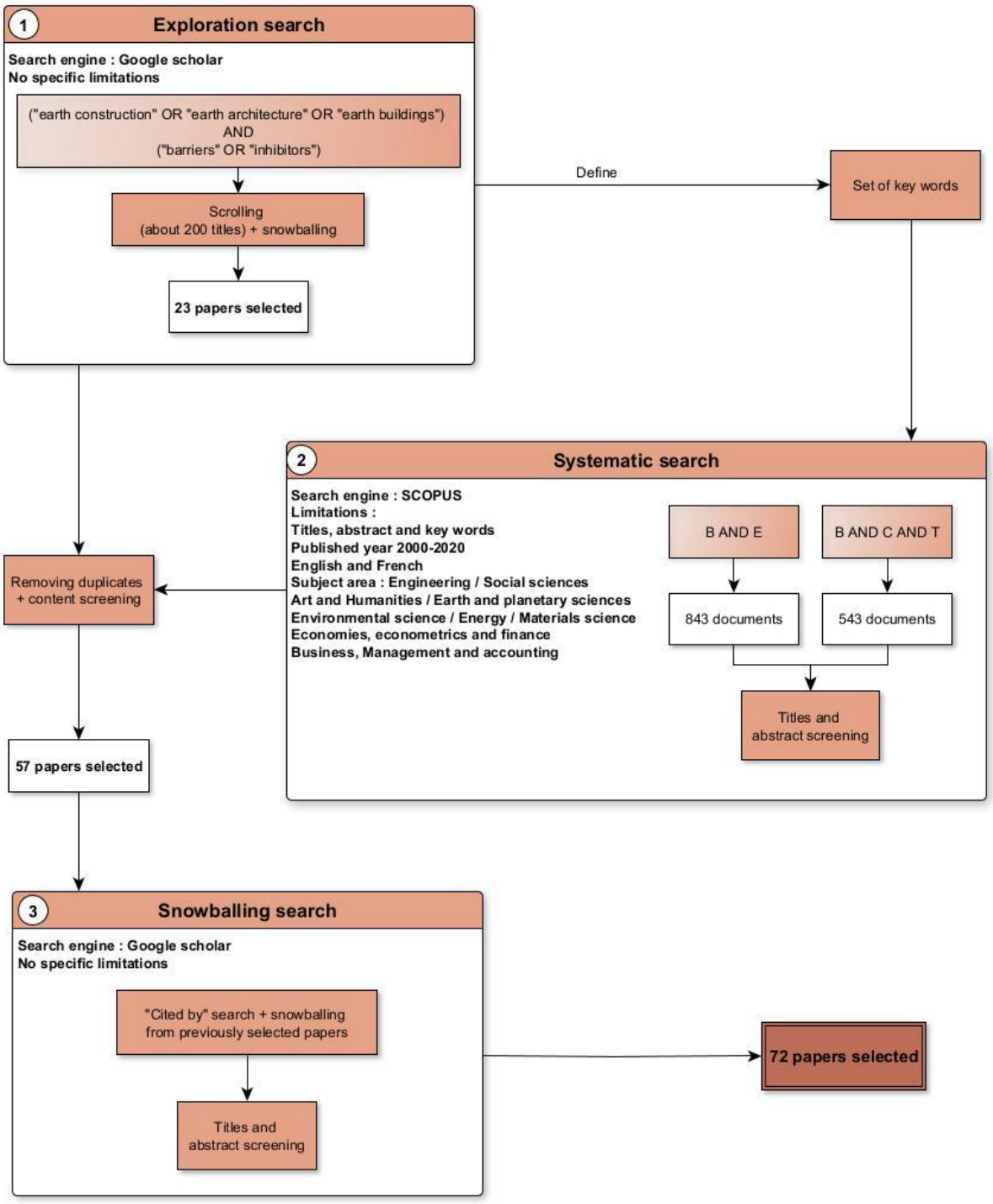


Figure 2.35: Detailed scheme of the different steps for the data collection

2.2.1. Search engines used for the review

The data collection process used Google Scholar and Scopus as search engines. The first is a wide search engine enabling access to a large variety of documents, whether peer-reviewed papers, thesis, or conference proceedings among others (Li et al., 2010). The advantage of Google Scholar is its theoretically complete coverage of any academic papers, including from economically developing

countries (Onyancha and Ocholla, 2009). However, this search engine does not meet the 27 criteria established by (Gusenbauer and Haddaway, 2020)[63] and thus, cannot be used by itself for a systematic search. In particular, Google Scholar results are presented by "*times of visits from users*", and not by an "*index of quality of the publication*" (Falagas et al., 2008), which might lead to bias in the selection of the data. On the contrary, Scopus meets the criteria to be used as a "*primary source*" for systematic search (Gusenbauer and Haddaway, 2020). Indeed, compared to its first competitor, namely the Web of Science, Scopus covers a greater number of journals (Chadegani et al., 2013). Therefore, Scopus has been chosen as the main source (step 2) and Google Scholar as a "*supplementary source*", used for the exploration search (step 1) and the snowballing search (step 3).

2.2.2. Exploration search – step (1)

For the first step, the exploration search was performed by using two types of search words: "earth construction", "earth architecture", "earth buildings"; and "barriers", "inhibitors". These two sets of search words were associated with the Boolean "AND". Not much attention was given to the search words for this first step, aiming to get used to the topic by reading a couple of articles related to it and not to exhaustivity. Amounts of 1430 documents were found and about 200 titles were screened through scrolling. Papers related to the barriers to the use of earth material in construction, such as "*Drivers and barriers of compressed stabilized interlocking earth blocks for building construction in Nigeria"* (Aghimien et al., 2016a) were selected. Then, other articles were selected through snowballing by reading their references and checking the section "cited by" with Google Scholar. A total of 23 papers were identified through this first process, which served as a preliminary study for the systematic search.

Ultimately, it has been observed that the use of "earth", as a search word, was too generic[64] and led to irrelevant documents, related to rare earth for example. Therefore, it has been decided to focus on techniques or types of materials associated with earth construction, aiming at covering all techniques. Based on the definition of the different earth techniques and material provided by (Maskell et al., 2016; Morel et al., 2021a; Schroeder, 2012), and the knowledge of the authors, the following set of search words related to earth construction techniques have been established: "rammed earth" OR "wattle and daub" OR **"**adobe**"** OR "Earth block*" OR "Soil block***"** OR "Clay block*" OR "mud block*" OR "Cob" OR "Clay plaster*" OR "earth plaster*" OR "Earth brick*" OR "Earth mortar*" OR "Clay panel*" OR "poured earth" OR "earthen infill" OR "extruded earth brick*". The purpose of diversifying

[63] Gusenbauer and Haddaway (2020) have established a list of 27 criteria's (including for instance Boolean functionality [OR, AND, NOT], parenthesis functionality but also the size of search engine) and compared 28 academic search systems through query-based method tests.

[64] See section 4.2.2.1 of the introduction of the thesis for a definition of "earth".

the search words related to earth construction was to cover correctly any type of literature related to earth construction. Moreover, some search words, such as “adobe”, “soil block*” and “clay block*”, were treated individually, to consider potential different meanings. Finally, the lack of international terminology in earth construction field (Schroeder, 2018) led the authors to think about the potential missing techniques described above and to test the following set of search words: “Earth*/Soil/Clay construction” OR “Earth*/soil/clay architecture” OR “Earth*/soil/clay building*” OR “earth* material”. Table 2.5 synthesis the search words used for the study.

Table 2.5: Search words used for the study

Search words used			
B (Barriers)	*C (Construction)*	*T (Techniques)*	*E (Earth)*
B = {B1 OR "Factor" OR "limit*"}* *B1 = {"Barrier*" OR "inhibitor*" OR "obstacle*" OR "hurdle*" OR "hindrance" OR "driver*" OR "blockage*" OR "impediment" OR "challeng*" OR "blockade*" OR "hinder"}*	*C = { "Construction*" OR "Building*" OR "Architecture*" OR "Structure*" }*	*T= {T1 OR "adobe" OR "Soil block*" OR "clay block*" OR T2}* *T1 = {"rammed earth" OR "wattle and daub" OR "Earth block*" OR "mud block*" OR "cob" OR "Clay plaster*" OR "earth plaster*" OR "Earth brick*" }* *T2 = {"Earth mortar*" OR "Clay panel*" OR "poured earth" OR "earthen infill" OR "extruded earth brick*"}*	*E = { "Earth* construction" OR "Clay construction*" OR "Soil construction*" OR "Earth* building*" OR "Clay building* OR "Soil building*e OR "Earth* architecture" OR "Clay architecture" OR "Soil architecture" OR "Earth* material*"}*

2.2.3. Systematic search – step (2)

Based on the search words previously defined, a systematic search has been performed using Scopus, following search criteria to limit the scope of the search. Assuming that barriers related to the use of earth material may change over time, and as present day and recent years were of interest for this study, a time limitation was applied, focusing on the last 20 years. From the exploration search (step 1), it was assumed that quite a few documents would be selected at the end of the process. Then, as it is recommended to include unpublished literature (such as conference proceedings or other ‘grey’ literature) (Schlosser et al., 2007), the authors have decided not to apply any limitation on the type of documents. The search was performed on “*titles, abstracts and keywords*” and was limited to “*English*” and “*French*”, as those are the two languages spoken by the authors. Finally, the subject area was restricted to: “*Engineering*”, “*Social sciences*”, “*Art and humanities*”, “*Earth and planetary sciences*”, “*Environmental science*”, “*Energy*”, “*Economies, econometrics and finance*”, “*Multidisciplinary*”, “*Business, Management and Accounting*” and “*Materials science*”. The subject areas have been chosen by: looking at the ones of the papers previously selected (step 1); rejecting irrelevant subject areas (e.g. “*Neuroscience*”, “*Psychology*” or “*Pharmacology, Toxicology and Pharmaceutics*”); and keeping sufficient variety to avoid missing papers.

Then, for each set of search words tested, the authors screened the titles and abstract using Scopus "*show all abstract*" configuration. They also assessed the eligibility of the documents by checking the meaning of the abstracts and their relevance to the research question. A total of 1386 documents were screened.

After removing duplicates, the content of the selected documents (both from exploration search and systematic search) was fully read to verify if the documents contributed to the research question, from which 57 papers have been selected.

2.2.4. Snowballing search – step (3)

Finally, to validate the set of keywords and crosscheck if other relevant literature were available, a third step was carried out. The backward snowballing search screened the references of each selected paper. Additionally, the section "cited by" on Google Scholar was used for each paper selected as a forward snowballing. As a result, ten papers were identified but only one was available on Scopus and was dedicated to local materials in general, not specifically to earth material (Dosumu and Aigbavboa, 2020). This last step validated the systematic search performed on Scopus. The study has finally been updated to October 2023. In conclusion, following the three steps, 72 documents were selected (Figure 2.35). Besides, at the end of the process, 5 theses treating, at least partially, the topic of barriers and drivers to the use of earth in construction were identified.

2.2.5. Data analysis

After collecting the data, the first step was to read the content of all the studies to become accustomed to the research question. This step allowed the rejection of articles that were too far from the scope of the study: for instance, one article was focusing on one type of architectural style (earthship) (Booth et al., 2021), although using earth material, the scope of this study was too wide considering our research question. Another example is an article that focused on the technical drawbacks of life cycle assessment on earth mortar (Santos et al., 2021). Although this study was valuable, the focus was too narrow for our interest.

Then, the articles were implemented in a qualitative research analysis software (Nvivo) and analysed through a process of coding. A thematic analysis was then performed by assembling these codes, using five categories: technical, economic, organizational, political and socio-cultural. These categories were already chosen to describe barriers to the use of earth in construction in previous studies (Morel et al., 2021a) and a rationale for the choice of these categories for the current PhD report is provided in Chapter 3 section 3.2.1.

For validation of this thematic analysis, the codes and themes were constantly discussed back and forth with the supervisory team.

2.2.6. Limits and validity of the method

Different criteria can be accounted for evaluating the limits and assess the validity of the literature review. For the appraisal of systematic reviews, some have been proposed by Schlosser et al. (2007), notifying that variability in the type and relative importance of these criteria can exist depending on the type of reviews. The following table (Table 2.6) synthesizes the criteria, and underlines the actions taken to address those. It would help to reduce the potential bias of the study (Schlosser et al., 2007).

Table 2.6: Description of criteria to assess the quality of the review and actions taken by the researcher to address potential biases

Criteria	Description	Actions
Protocol	A clear protocol should be described including mainly: criteria for selecting studies; search strategies for identification of studies; methods of the review. Schlosser et al. (2007) advice to refer to existing protocol	Section I.1) refer to the PRISMA-P protocol of literature reviewing. Detailed insights on the protocol applied were described in previous sections.
Question	"The topic that a systematic review aims to address should be clearly expressed in a concise question or hypothesis" (Schlosser et al., 2007)	Clear and concise research questions have been addressed for this chapter: Are there barriers to the use of earth in construction? What are the barriers and drivers to the use of earth in construction?
Sources	Different biases can come from the sources used to identify the relevant studies, including: - database bias (relying on wrong or too few databases);	- To avoid database bias, two complementary databases have been used (Google Scholar and Scopus), see section 2) Data collection and analytical method

	- source-selection bias (resulting from a limited investigation of available source types) - Publication bias (Include only published studies)	- To avoid source-selection bias, different selection methods have been applied including selection through criteria on the database and selection through snowballing (see section 2) Data collection and analytical method) - An attempt has been highlighted to find unpublished studies, in particular through discussion with professionals in earth construction and searches on Google engine
Scope and selection principles	"Scope and selection principles are primarily expressed as the inclusion and exclusion criteria for studies in review" (Schlosser et al., 2007). These principles should thus be highlighted in the methodology and discussed. They might introduce different biases depending on the types of constraints used: geographic; temporal; linguistic; study-design restrictions; population; intervention; and outcome. These criteria also refer to insights into the reliability of the selection of studies and the log of rejected studies.	No restriction has been applied on: geographic; study design; population (e.g. age, gender, …); intervention; or Outcome. Indeed, these constraints were not relevant to this study, stemming from the fact that the study of Schlosser et al. (2007) has some specificities for medicine discipline. However, temporal (between 2000 and 2023) and linguistic restrictions have been applied. Considering the research question focusing on the present day, temporal restriction did not raise issues except for the potential to miss recently published studies. To avoid it, a continuous watch on newly published research referring to the research questions was performed. Linguistic restrictions meanwhile are

		obviously biased as only the two languages (English and French) spoken by the researcher were selected. Studies in other languages might thus have been missed and readers should be aware of it. To improve the reliability of the selection of studies, the research has been run two times with a one-year's delay. Finally, as recommended by Schlosser et al. (2007), rejected studies from the last selection step were mentioned.
Data extraction	"A clear outline of the process by which the data was extracted from the original studies" (Schlosser et al., 2007) should be provided	The analysis protocol is described in the previous section.
Quality assessment	"Because a systematic review can only be as sound as the included studies, an investigation of the quality of those studies is an important component of the data extraction and appraisal process" (Schlosser et al., 2007)	The study's limitations and quality are discussed in the following section II.1), focusing in particular on the methodology employed. Moreover, a thorough discussion is provided in sections II.4) and II.5) on the different approaches and limitations of the selected studies in addressing the research question.

2.3. Conclusion of the section

This section described the methodology employed for the literature review. The method was based on a systematic search and review approach including three steps of data collection (exploration,

systematic, and snowballing search), using two different search engines (Google Scholar and Scopus). 72 papers, including peer-reviewed articles, conference papers, book chapters and master's thesis were selected along with 5 theses. These papers were categorized into four groups (Appendix B): (1) articles identifying the barriers and drivers affecting the use of earth in construction by using a specific methodology; (2) papers investigating one type of barriers or drivers; (3) papers having only a subsection or notification addressing barriers and drivers, or papers referring to them but without specific methodology used to establish scientific evidence; And finally (4) while peer-reviewed journal articles were gathered into Groups 1 to 3, Group 4 corresponds to all the rest of the literature, including conference proceedings, master's thesis, reports and book chapters. This underscores differences in quality of the papers selected which will be discussed in the next section.

Finally, these papers were analysed following a thematic analysis, based on a coding process and the use of the qualitative analysis software Nvivo. The barriers and drivers identified were then categorized under technical, economic, political, organizational and socio-cultural categories. This will be discussed in section 4.

3. Results, data limitation and quality

The results of the data collection are presented in Appendix B. For each article, different information was notified: the author's name; the year of publication; the object of the paper; the name of the journal, alongside its classification on SCIMAGO ("Scimago Journal & Country Rank," 2020); if relevant, the location of the study, referring to countries code following the norm ISO 3166; the types of economies associated with the location, categorized into "high-income countries", "low-income countries", "upper-middle-income" and "lower-middle-income" countries following a report of United Nation (UN, 2020); if relevant, the earth techniques for which the papers referred to are notified, as well as the use of stabilizers; finally, the type of methodology (Qualitative, quantitative, or mixed), and the research method alongside some details were highlighted. These information and categorizations helped to highlight the limits of the data collected, which will further be discussed.

The first result consists in highlighting the number of publications on the topic per year. Although the number of publications remains quite low, Figure 2.36 shows a growing interest in the research question over the last decades.

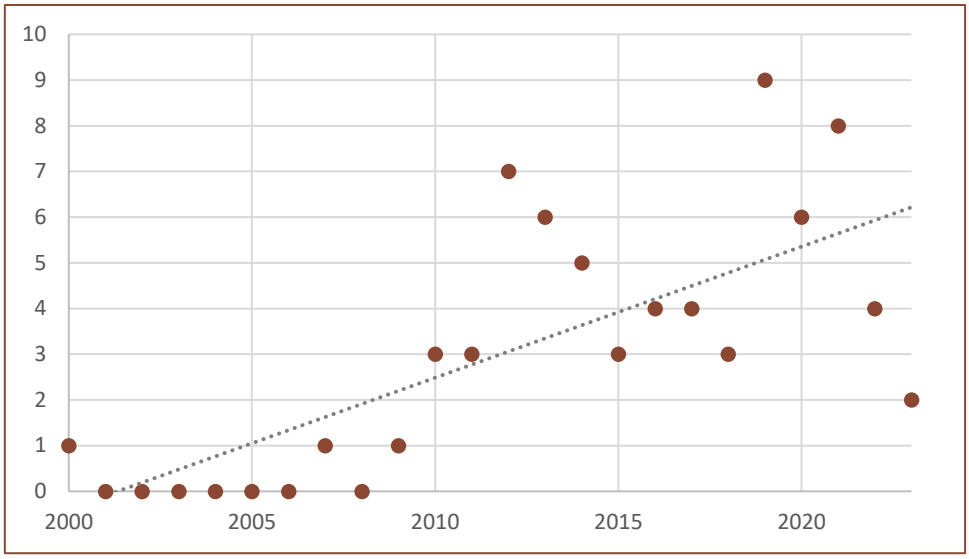


Figure 2.36: Studies investigating barriers and drivers to the use of earth in construction on the two last decades

3.1. Type of document

To assess the scientific quality of the data, the first approach consisted in assessing the type of document covered by the systematic search. Indeed, although conference papers can provide useful information, a peer-review process assuring some level of scientific quality is sometimes lacking. Similarly, book chapters and reports, constituting grey literature (Flick, 2015), cannot be considered on the same level as peer-reviewed journal articles with respect to the quality of scientific evidence.

The data collection process led to selecting 53 journal articles, composing the large majority of the data set, 12 conference papers, 4 book chapters and 2 reports (Figure 2.37a). Regarding journal articles, only half of them were published in high-ranked journals (Figure 2.37b). It is worth noting that high-ranking journals do not necessarily assure high-quality papers. An example could be the fraudulent study published in The Lancet during the Covid period in 2020, then retracted (Mehra et al.,

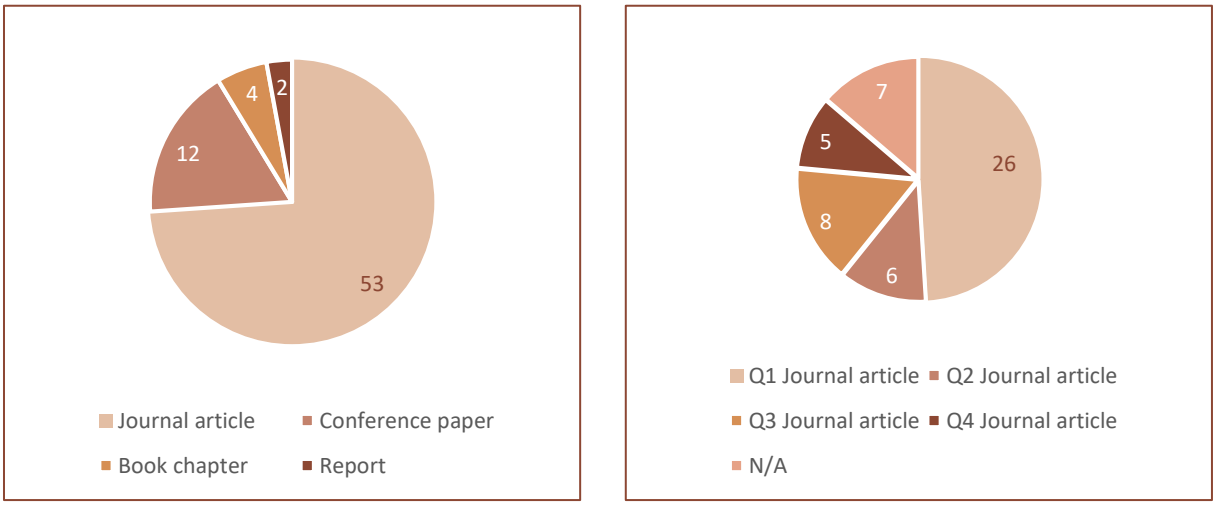


Figure 2.37: (a) type of documents studied (b) journal article according to the ranking of the journal

2020). However, consulting the rank of the journal still provides interesting first information, as we can suppose the process of peer-reviewing has a greater quality for Q1 journal articles than for Q4 journal articles. On the contrary, articles published in Q4 journals are not necessarily synonymous with low scientific quality. Looking at a journal's quality can only be seen as a first insight into the quality of the reviewed article and then require looking thoroughly at the methodologies used in these studies.

3.2. Methodologies applied

Regarding the methods employed in the papers analysed in this study, qualitative (23%), quantitative (17%) and mixed (14%) analyses have been used in similar proportions throughout the data (Figure 2.38). Various types of methodologies were employed, such as questionnaire surveys (see for example (Danso, 2013; Niroumand et al., 2013; Shahabadi et al., 2018), interviews (see for instance (Morel et al., 2021a; Samarasinghe and Falk, 2022), case study analysis (see for example (Cataldo-Born et al., 2016; Lu and Liu, 2013; Sameh, 2014; Zawistowski et al., 2020) or even Delphi method (see for example (Mohammad Sharif Zami, 2021; M. S. Zami, 2021a)).

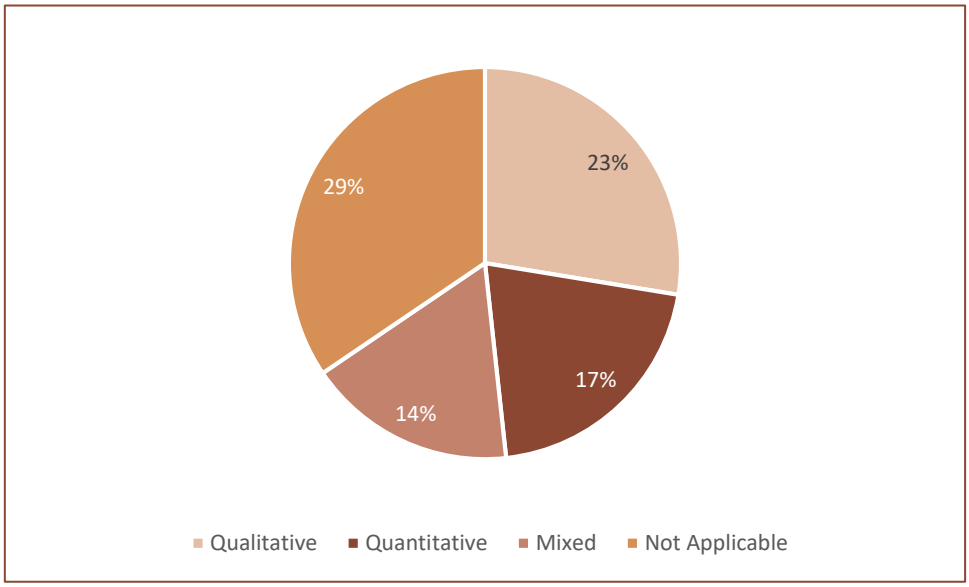


Figure 2.38: Types of methodologies used in the papers reviewed for the thesis

The authors faced many papers having an unclear methodology, where sometimes a dedicated section was lacking (29% of the documents, illustrated as "not applicable" in Figure 2.38). For instance, in the papers using the questionnaire's method, the response rate was most of the time either missing (El-Sawalhi and Ajwa, 2013; Kraus, 2012) or very low (Hadjri et al., 2007; Spišáková and Mačková, 2015a). The response rate corresponds to the percentage of participation in a study (Bryman, 2016a, p. 199). It indicates the non-responses and therefore is an important parameter to assess the validity of the data. Indeed, the lower the response rate will be, the higher the non-responses and the lower the representativity of the results. Table 2.7 represents the response rate for the study that used a

questionnaire survey as methodology. Some of the response rates were calculated from the information provided in the papers.

Table 2.7: Response rate provided or calculated in the papers that have used questionnaire's survey as the methodology

	Author	Year	Response rate (RR)
Group 1	Lakys et al.	2022	Discussion on RR but couldn't be calculated
	Dorado et al.	2022	RR = 65%
	Ben-Alon et al.	2020	No RR
	Shahabadi et al.	2019	No RR
	Spisakova and Mackova	2015	RR = 22%
	Owino et al.	2014	RR = 88%
	El-Sawalhi and Ajwa	2013	No RR
	Foruzanmehr	2013	No RR
	Niroumand et al.	2013	RR = 51%
	Danso	2013	RR = 76,9%
Group 2	Hughes et al.	2017	No RR
	Hadjri et al.	2007	RR = 37%
Group 4	Aghimien et al.	2016	RR = 95%
	Kraus	2012	No RR
	Wright and Thorpe	2015	RR = 4%

Most of the papers that have used case studies analysis as methodology have quite low quality. First, only two papers have been published in Q1 Journals, among which one used case studies just as references without thorough and scientific analysis (Sameh, 2014). Second, some of the papers have no dedicated methodological section (Bradley and Gohnert, 2018; Lu and Liu, 2013). Besides, the buildings investigated by these studies are mainly small housing (see Table 2.8). The case investigated in this thesis (a two-storey office building) is therefore unique in the literature (in term of size and program), highlighting the originality of this thesis.

Table 2.8: Studies that investigate the research question using case study analysis as a methodology

	Author	Year	Type of document	Type of case study
Group 1	Zawistowski et al.	2020	Q2 Journal article	One building (one storey)
	Totla et al.	2019	Q4 Journal article	One building (house)
	Bradley et al.	2018	Q3 Journal article	Three typologies of masonry buildings (low-cost housing)
	Cataldo-born et al.	2016	Q3 Journal article	Simulated building (housing) / barriers were studied through a literature Review
	Sameh	2014	Q1 Journal article	Four buildings but used more as references than a thorough study of those cases
	Lu and Liu	2013	Q4 Journal article	Traditional earth buildings
Group 2	Hurol et al	2014	Q1 Journal article	Two buildings (housing)
	Hadjri et al.	2007	Q3 Journal article	Two case studies (housing)
Group 4	Baiche et al.	2017	Conference	Two villages with earthen housing
	Van der Linden et al.	2019	Conference	Two buildings (a classroom and a watchtower)
	Dick and Krahn	2015	Book chapter	Two buildings (one-storey and two-storey single-family dwellings)

In conclusion, this part shows that only a few well-structured scientific papers discuss the research question.

3.3. Previous thesis

A couple of theses have been published recently more or less related to the research question, in different disciplines (Table 2.9). To highlight the originality of this PhD thesis, it is important to position it in relation to previous work. This will be done through the manuscript but this section aims at providing first insights on previous thesis work.

Table 2.9: Different PhD thesis related to the research topic

Author	Year	Title	Discipline
Y. Kulshreshtha	2022	Building affordable, durable and desirable earthen houses	Civil engineering
L. Ben-Alon	2020	Integrating earthen building materials and methods into mainstream construction	School of Architecture
V. Villain	2020	Sociologie du champ de la construction en terre crue en France (1970-2020)	Political science
H. Gasnier	2019	Construire en terres d'excavation, un enjeu pour la ville durable	Architecture
G. Bosman	2015	The acceptability of earth-constructed houses in central areas of South Africa	Architecture

Bosman (2015) investigated the current perceptions of earth-building techniques (in particular adobe) from a household perspective, through the use of a qualitative and quantitative survey, with a focus on central areas of South Africa. The aim was to identify "*the factors that can be addressed in order to make earth-constructed houses in general more acceptable*"(Bosman, 2015). One main result of his study is highlighting the negative attitudes, related to water sensitivity, toward earth techniques from households.

Gasnier (2019) have studied the potential use of earth in a very specific context: reusing excavated earth from the excavation work of the "Grand Paris" project[65]. This thesis aims at answering two research questions: "*Is it relevant to transform the excavated earth of the construction site of major urban centres into a resource for architecture and what are the potentials for the construction of a sustainable city?*" (Gasnier, 2019, p. 8). The purpose of this study is more to describe the process of reusing excavated earth in Paris than to describe barriers and drivers to the use of earth in construction. However, some sections, still limited, were interesting for this PhD thesis. In particular, on pages 56 to 59, the author, based on interviews, described briefly some "*constraints*" to the use of earth in construction.

Another PhD thesis published in the French context is Villain (2020), in political science discipline. This thesis reports the history of earth construction in France from 1970 to 2020, in particular in Brittany

[65] The "grand Paris" project is an urban development project aiming in particular at the construction of a new metro line "grand Paris express". Considerable amount of waste, mainly earth, will be generated for this project requiring consideration of the potential reuse of those earths.

and the region of Lyon, from the perspective of Bourdieu's theory of social fields[66]. Doing so, he investigated the creation, autonomization and structuration of the earth construction field in France. In that field, he analyzed the different groups of professionals and their social interactions, identifying five distinct groups carrying different visions of earth construction and mainstream construction. This thesis was particularly useful to understand the situated vision carried by professionals (including researchers) and will be used, in particular, for the section 5 of this chapter.

The study by Ben-Alon (2020) focused on describing the potential of the integration of earthen building materials and methods into mainstream construction. In particular, she investigated "gaps" in the implementation of earthen construction by interviewing ten experts (architects, civil engineers, builders and teachers, and regulatory experts). Then, she studied more thoroughly the barriers and motivation to the use of earth based on a survey (Ben-Alon et al., 2020b, pp. 83–94). This survey was conducted worldwide.

Finally, and most recently, Kulshreshtha (2022), investigated the potential of earth construction for low-cost housing in India. In particular, he has conducted a field survey in India to "*understand factors favouring or limiting construction and daily use of earthen houses*" (Kulshreshtha, 2022). Besides, he has studied the potential of bio-based additives (such as cow-dung) on water resistance of CEB. Finally, he developed YouTube videos and assessed the effectiveness of such communication medium to disseminate scientific knowledge. Although very interesting, this study focused on the Indian context and its interest for the present PhD thesis (focusing on the French context) is therefore limited.

3.4. Conclusion of the section

This section has highlighted a growing interest on the topic of barriers and drivers ot the use of earth construction in the last two decades, with a growing number of publications. The quality of these however have been discussed. Indeed, while a majority of the papers selected was peer-reviewed articles, only half of it was published in high-ranked journals. Different methods approach was found in similar proportions: 29 % for qualitative approaches, 23 % for quantitative and 17 % for mixed methods. The quality of these methods has been discussed. In particular, the ones using case studies analysis were identified of low quality. This highlight a research gap and is one justification to the interest of choosing this method for the thesis (see Chapter 3).

[66] Bourdieu's theory of social fields is a sociological concept that describes the social world as a set of distinct and autonomous fields, each governed by its own rules and logic. These fields represent specific domains of social life, such as education, art, politics, and economics, and are characterized by the struggle for power and resources among individuals and groups. Bourdieu argued that agents within these fields (individuals, institutions, etc.) engage in a constant pursuit of social capital and symbolic capital, which grants them legitimacy and influence within the field. The theory highlights how social positions and interactions in one field can influence an individual's standing and strategies in other fields, shaping their overall social trajectory.

Finally, some insights were provided on the different thesis previously published and more or less related to the topic. Among which, two will be particularly useful for this thesis as dedicated to the French context (Gasnier, 2019; Villain, 2020). However, none of these theses has investigated the design and construction phase and building's scale to address the research question.

4. Discussion of the identified factors in the literature

The factors affecting the use of earth identified in the literature will now be discussed. Rohracher (2001) advises considering the technical, organizational, political, and economic factors and the strategies of the stakeholders. In this thesis, the four first categories will be taken and the last one replaced by sociocultural factors. Indeed, socio-cultural aspects have already been underscored to have a crucial influence on the diffusion of innovation in the building sector (Deshayes, 2012), and in earth construction in particular (Hafez et al., 2023). Besides, these five categories (technical, economic, political, organizational and socio-cultural) have been recommended by authors in earth construction field (Morel et al., 2021b). These categories correspond to themes generated from the data. To simplify the discussion, each category of factor will be described in distinct parts. However, it is worth noting that these factors are interrelated, as already highlighted by some authors (Ben-Alon et al., 2020a). This interrelation will be discussed in section 4.6.

The results per categories have been assembled in Table 2.10 highlighting that the different categories of barriers seem to be cited in similar proportions (see Figure 2.39 for the number of papers that cite the different categories of barriers in group 1 of the literature studied). Although useful, a quantitative approach is limited on the analysis of barriers and drivers. Indeed, a barrier could be less cited but still have a great importance or influence on other barriers. Therefore, a detailed discussion is required that will the purpose of this section.

Table 2.10: Number of papers (group 1) mentioning the different sub-categories and categories of barriers

Categories	Sub-categories	Number of papers
Technical	Resource	9
	Environment and climat	2
Economic		
	Labor intensity	5
	Market	5
Political	Difficulties to obtain insurance	3

	Inadequate regulation	7
	Lack of governmental support	8
Organisational	Process	9
	Coordination	3
	Communication	1
Socio-cultural	Skepticism	4
	Resistance to change	4

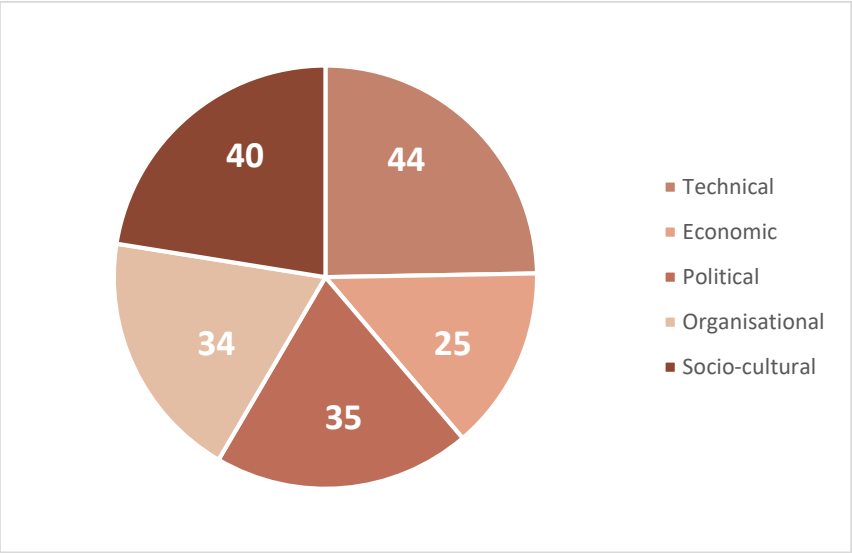


Figure 2.39: Number of papers (group 1) addressing each category

4.1. Technical factors

Different technical factors affecting the use of earth in construction were identified, whether related to the material resource, the material's properties, and the design, construction and maintenance phases.

The resource-related barriers include the potential inadequacy of local earths. Indeed, some authors argue that local earth does not always meet the recommended proportion of clay, silt, sand and gravel (Gallipoli et al., 2017). Finding available and suitable earth is sometimes a challenge, particularly in urban areas (Wright and Thorpe, 2015). Some authors also highlighted the need for hydraulic adjuvantation when the granulometric and clay content is not suitable for a specific technique, such as Compressed Earth Blocks (CEB) (Dorado et al., 2022). Finally, the earth variability, as a natural

material, also has been reported as a barrier (Lu and Liu, 2013), where the construction industry is more used to highly standardised materials (Harries et al., 2020), such as reinforced concrete. Adapting the technique and architecture to the earth available locally might help to overcome this barrier (see Figure 0.15). Indeed, some authors have recently concluded that, in the UK, the availability of earth might not be considered a barrier (Mohammad Sharif Zami, 2021). The issue of finding and quantifying the material resources has been addressed by some authors who have developed a method in the case of cob in the European context (Hamard, 2017). It has also recently been shown that looking at grain proportions might be unsuitable to characterize earth for earth construction (Rojat et al., 2020), where clay activity and proportion of the fine part should be preferred, at least for rammed earth.

Various barriers related to material properties, such as the durability[67] of the material were reported as a major concern (Danso, 2013; Hadjri et al., 2007; Kulshreshtha et al., 2020; Monzur, 2018; Owino et al., 2014a). Many authors reported the low water resistance of earth material as a barrier (El-Sawalhi and Ajwa, 2013; Hadjri et al., 2007; Hughes E. and Elliott W. J., 2017; Monzur, 2018). Similarly, low strength has also been highlighted as an obstacle (Danso, 2013; Hadjri et al., 2007; Monzur, 2018; Zami and Lee, 2011a). Indeed, compared with conventional materials (such as concrete or fired brick), earth material has low strength. For example, a wall made with rammed earth has a compressive strength of 0.5 to 2 MPa (Walker et al., 2005), which is at least ten times less than concrete. The low strength might be an issue, particularly in urban areas, when a high density is required (Wallis, 2012). The weak resistance to earthquakes has also been identified as a limitation of the use of earth material (El-Sawalhi and Ajwa, 2013; Zami and Lee, 2011a). Finally, another barrier identified throughout the literature is termite and rodent infestation (Danso, 2013; Kulshreshtha et al., 2020; Monzur, 2018).

The durability of the material is highly dependent on the climatic conditions, especially for unstabilised earth material (Gallipoli et al., 2017), wherein dry climate earth material has shown suitable durability. Besides, a loss between 1 and 2.5 % of thickness on 40 cm thick rammed earth walls over 20 years has been observed in wet continental climates (Q.-B. Bui et al., 2009b). Related to durability, some authors highlight inappropriate climate conditions acting as a drawback (Zami and Lee, 2011a). Areas with dry and hot continental climates show an optimal use of earth material properties compared with tropical and alpine climate conditions (Niroumand et al., 2013). Choosing the appropriate earthen technique regarding the climate conditions might solve this issue (Mileto et al., 2019). Besides, the material sensibility to climate conditions sometimes imply a specific construction period (avoiding winter). This issue might be overcome by using indoor prefabrication instead of on-site fabrication (Zawistowski et

[67] Durability can be defined as “the ability of a structural element to resist environmental or anthropogenic wear, damage or decay.” (Beckett et al., 2020)

al., 2020). Most of the barriers regarding the material properties were specific to low-income and lower-middle-income countries and could generally be explained by an improper design of traditional dwellings (lacking proper foundations, as an example), as described by (Kulshreshtha et al., 2020) in India.

Related to durability, one of the most cited barriers is the need for regular maintenance (Ben-Alon et al., 2020a; Danso, 2013; El-Sawalhi and Ajwa, 2013; Foruzanmehr, 2013; Kulshreshtha et al., 2020; Monzur, 2018; Zami and Lee, 2011a). On the contrary, recent authors, based on qualitative and quantitative survey among 48 professionals in Australia, established that Rammed Earth requires low maintenance (Strazzeri and Karrech, 2023). However, the authors don't specify if it is concerning cement adjuvanted or unadjuvanted rammed earth. Further research could be carried out on this notion of maintenance as it is directly linked to the supposedly low durability of the material. Besides, experts believe that this barrier can be overcome by a proper design (Ben-Alon et al., 2020a) or by considering cyclical maintenance of the building in the design (Moriset et al., 2021). Moreover, the maintenance of earthen techniques is sometimes easier than for conventional equivalent techniques, for example for interior earthen plasters (Moriset et al., 2021).

Finally, A commonly cited barrier is the lack of scientific data, research and capitalisation, related to the lack of research funding (Mohammad Sharif Zami, 2021) and the lack of internationally standardised test procedures (Ben-Alon et al., 2020a; Zami and Lee, 2011a). The latter is more significant when reminding that some authors recommend establishing a testing program while designing an earthen building (Canivell et al., 2020), and where the lack of quality control is seen as a barrier (Gallipoli et al., 2017). This issue has been highlighted particularly for CEB production at small and medium-scale where the equipment is sometimes not available nor the financial resources to perform laboratory testing, lowering eventually the quality of the blocks (Dorado et al., 2022). Nowadays, there are still difficulties to relate laboratory parameters to on-site performances of the material or building, for instance, the assessment of the compressive strength (Morel et al., 2021a). To fill this gap, the "274-TCE[68]" RILEM Technical Committee is developing pre-standard testing procedures, emphasizing the need to preserve the multifunctionality of the material (274-TCE, 2021).

Concerning the design, the combination of the earth with other materials needs to be carefully considered, in particular, the earth material drying process being time-consuming can create conflict with other materials (Gasnier, 2019, p. 57). The lack of technologies (Mohammad Sharif Zami, 2021; Zami and Lee, 2011a), and the lack of good technical support (Samarasinghe et al., 2020) are also

[68] Testing and Characterisation of Earth-based building materials and elements.

barriers identified in the literature. Finally, the size and complexity of modern buildings is also an obstacle when using earth material (Morel et al., 2021a).

Conclusively, the technical barriers described in the literature could actually be referred to as limits of the material instead of "barriers". Indeed, most of those technical "*barriers"* could be overcome by a proper design. Therefore, overcoming these technical limits seems more a matter of education to which appropriate educational programs could help. Meanwhile, presenting these technical limitations as "*barriers"* tend to invite overcoming these by increasing the performance of the material. However, as the proper design might be sufficient in most cases, then the approach of increasing the performance might not be the priority. Therefore, the new users, (including all the asset lifecycle stakeholders) and end-users, who intend to engage with this type of architecture, should be aware that the construction and maintenance of earthen buildings are different from any conventional construction buildings. In that sense, two types of technical barriers can be considered: (1) those that could be overcome by a proper design for which educational programs could be created including the design specificities of the earth construction; and (2) the technical barriers related to a lack of knowledge about the broad range of behaviour expected. For the latter, future researchcould determine behavioural rules which could then inform educational programs.

Interestingly and as already discussed in the general introduction of this thesis, technical limitations, such as the difficulties to understand the behaviour of the material, are often highlighted in abstracts (or introductions) to introduce the research aim of some papers (Q.-B. Bui et al., 2009b; Chauhan et al., 2022; Laou et al., 2021). However, it is worth noting that technical barriers are only the tip of the iceberg. Indeed, looking at barriers and drivers to the use of earth in construction requires looking at other types of barriers, such as economic, political, organizational or sociological (Morel et al., 2021a). This was actually recommended by some earth construction practitioners as illustrated in a quotation in the thesis of Villain (2020):

> *"We assert that* ***issues related to ecological construction are not merely technical but, above all, political, cultural, or social****... In other words, we implicitly express that ecology without significant political changes in modes of production and economic understanding appears to us to be nothing more than superficial patches without real impact." (Villain, 2020, p. 381)*[69]

[69] Translated by the author from French to English. Original version: « *Nous affirmons que les questions liées à la construction écologique ne sont pas seulement techniques, mais avant tout politiques, culturelles ou sociales... Dit autrement, nous exprimons implicitement qu'écologie sans changements politiques majeurs dans les modes de production et dans l'appréhension économique nous semble n'être que rustines sans impact réel.* »

This quotation was extracted from a meeting minute of the network Ecobâtir[70], dating from 2017, initially accessible on the Internet but not anymore.

4.2. Economic factors

The earthen architecture also faces economic barriers, according to the literature, as extra costs highlighted as a major drawback (Ben-Alon et al., 2020a; Kulshreshtha et al., 2020; Owino et al., 2014a; Strazzeri and Karrech, 2023; Mohammad Sharif Zami, 2021; Zami and Lee, 2011a). The different costs of earth construction can be categorized under "*material costs*", "*production costs*" and "*construction costs*" (Williams et al., 2010). Although the material cost might be cheap as it is locally available and it is a waste in construction, in low to middle-income countries, the extra costs can come from the use of adjuvants (Kulshreshtha et al., 2020). In these countries, without adjuvantation, the low price of earth constructions is generally perceived as a driver for affordable housing for many authors (Abu-Hammad, 2011; Adegun and Adedeji, 2017; Adeniyi and Mohamed, 2019; Bradley and Gohnert, 2018; Egenti et al., 2014; Gado et al., 2010; Totla et al., 2019). In high-income countries, different reasons can explain these extra costs, mainly related to production and construction costs: the lack of building codes, increasing engineering costs and construction time (Ben-Alon et al., 2020a); the high labour prices (Williams et al., 2010; Zawistowski et al., 2020), related to the labour intensity of earth construction (Ben-Alon et al., 2020a; Danso, 2013; El-Sawalhi and Ajwa, 2013; Zami and Lee, 2011a), for example in France, the tax system burdens more on labour than raw materials (Villain, 2020, p. 226); and the small scale of production (Williams et al., 2010). Labour intensity can represent however an opportunity for job creation (Zami, 2020b). Perceived higher upfront costs (Danso, 2013; El-Sawalhi and Ajwa, 2013) and unexpected costs (Ben-Alon et al., 2020a) are also barriers identified in the literature. In high-income countries, different ways to reduce costs could be considered: scaling up production and making it more industrial (Van der Linden et al., 2019a) or accepting the additional costs factoring in the environmental benefits and values of earthen constructions (Villain, 2020, p. 227), by using fiscal incentives for instance. Concerning the latter, in France, in his PhD, Villain (2020) has highlighted different arguments used by professionals to support earth construction despite the potential higher costs, such as: balancing the higher costs by reducing the size of the building or abandoning some costly equipments, to use earth and profit of its benefits; or explaining to public clients the fiscal benefits of employing local professionals to build with earth (Villain, 2020, p. 226).

Another important factor affecting the use of earth materials in the construction sector is the lack of demand. In some countries (such as the US, India and Australia) earthen construction can benefit from an emulsion to the use of natural materials for their environmental benefits (Niroumand et al., 2013).

[70] Ecobâtir network was a network of committed earth construction practitioners.

This is particularly true in high-income countries, where new commercial interests in the material can be observed (T.M. Marsh and Kulshreshtha, 2021). Similarly, in middle-income countries, in the wealthy young population in Iran, the environmental characteristics of earth buildings are seen as a driver for the use of earth materials (Zare Shahabadi et al., 2019). However, there is still a general lack of client demand (El-Sawalhi and Ajwa, 2013; Hadjri et al., 2007; Spišáková and Mačková, 2015a; Mohammad Sharif Zami, 2021). Earthen construction is still a niche market that both acts as a barrier and represents an opportunity for some professionals, who try to obtain commercial benefits from the ecological image of the material. These professionals generally have to diversify their activity (for instance by providing training) to stabilise their company in the market (Dorado et al., 2022).

Finally, the use of local materials such as earth represents an economic opportunity in a globalized world. Indeed, due to transport restrictions during the COVID-19 pandemic, increasing prices on construction materials have been observed, while it was not the case for earth materials (Moriset et al., 2021).

Unlike the technical factors for which technology transfer can be done through the available scientific literature, for economic factors there is a lack of scientific studies to rely on. Therefore, research is needed on this topic, especially in the context of the circular economy and whole lifecycle cost. A recent thesis has actually investigated a coupled model of environmental and economic assessment of the reuse of excavated earth for earth construction (Higuera romero, 2023).

4.3. Political factors

Political barriers were identified whether related to inadequate or lack of regulations and the lack of government support. Indeed, one of the most cited barriers is the lack of codes and standards[71] (Ben-Alon et al., 2020a; Cataldo-Born et al., 2016; Dorado et al., 2022; Giada et al., 2019; Hadjri et al., 2007; Kulshreshtha et al., 2020; Strazzeri and Karrech, 2023; Mohammad Sharif Zami, 2021; Zami and Lee, 2011a). Although the number of new regulations and norms for earth construction has been increasing in recent years, particularly in high-income countries, the amount of codes and standards is still very low compared with conventional materials (T.M. Marsh and Kulshreshtha, 2021). This concerns also the protection of earth construction heritage, for which there is a lack of legislation as well (Zami and Lee, 2011a). This lack of codes and standards seems to be a major issue for designers because builders are generally more used to "*highly predictable standardized materials*" and less accustomed to earth

[71] A clear distinction should be made between code, regulations and standards. a code provides a comprehensive collection of laws or rules, regulations detail specific requirements and instructions to enforce those laws, and standards offer voluntary guidelines or specifications to achieve consistency and quality in a particular area. While regulations provide legal requirements that must be met, standards (or norms) guide, without an obligation to follow them, how to attain those requirements. Definitions of those terms are provided in Chapter 4.

materials (Dahmen and Ochsendorfs, 2012). For example, some authors described the need for structural engineers to make their research and develop new methods for each new earth building project, based on a time-consuming "*rule-of-thumb*"(Dick and Krahn, 2015; Krahn and Dick, 2019). To compensate for this lack of codes and standards and for a matter of insurability, technical certifications for earth material are occasionally required, which is a difficult, time-consuming, costly and sometimes biased process (Morel et al., 2021a). Other authors also reported professionals lack awareness of the existence of codes and standards (Kulshreshtha et al., 2020; Niroumand et al., 2013).

Eventually, the lack of codes and standards can also lead to environmental and structural incoherencies. To be able to design earthen buildings, designers need to stick to other regulations, such as concrete or masonry regulations. For instance, the theatre of Balaguer was built in 1992 with rammed earth walls of 50 cm thickness in an area with rammed earth building heritage. Although adjuvantation is not always relevant, in this region of Spain, the earth was traditionally adjuvanted with 5% of the weight of cement. However, to reach the concrete regulation requirements, designers had to increase this amount by 10% and then highly increased the environmental impact of the building for no advantage other than sticking to the existing codes (Delgado and Guerrero, 2006). Besides, in Cyprus for earthquake-resistant adobe structures, the application of inadequate regulations can imply less sustainable, less affordable dwellings or even new technical problems such as cracking due to interaction between concrete reinforcement and non-adjuvanted adobe (Hurol et al., 2015).

The creation of new appropriate codes and standards is generally seen as a driver for the use of earth in construction (T.M. Marsh and Kulshreshtha, 2021; M. S. Zami, 2021a). However, in some specific contexts, such as in India, the lack of codes also allows more flexibility to innovate in earth construction (Kulshreshtha et al., 2020).

A complicated process of creating new standards has also been identified (Dick and Krahn, 2015). To build new regulations, some authors recommend using existing traditional construction to define and adjust threshold normative requirements, for the selection of the material (Gomes et al., 2014). Besides, the lack of earth construction advocates in regulatory and standards commissions has also been reported as a barrier to the creation of new standards and regulations for earth in construction (Ben-Alon et al., 2020a).

In addition to the lack of regulations and standards, those that exist are sometimes inaccurate or inadequate (Fernandes et al., 2019). For instance, thermal regulations are generally not suited to the thermal performance of the earth. Indeed, the current disregard for the inertia of the material leads to an underestimation of its properties. Thus, buildings with suitable thermal comfort conditions may not meet the minimum thermal insulation requirements (Fernandes et al., 2019). Standards can also

underestimate the mechanical properties of the material. For instance, the German design rule (Dachverband Lehm e.V., 2009), as shown by Müller et al. (2017), seems to underestimate the load-bearing capacity of earth block masonry units (EBM). Moreover, this guideline considers a global safety factor, highly conservative for EBM, regardless of the differences in manufacturing or differences in earths. This method of design leads to an underestimation of EBM load-bearing capacity and then to higher costs, due to the increased wall thickness (Müller et al., 2017). Other barriers related to inadequate regulations and norms systems include the difficulty to obtain a building permit and insurance (Ben-Alon et al., 2020a). The difficulty of obtaining insurance is sometimes linked with an unsuitable insurance system, as in France (GT biosourcés action 18c, 2012), but also with a conservative regulatory system. For example, in Spain, to obtain 10-years insurance, which is required for some categories of buildings, insurance providers are assessed through the "*Technical Control Organizations*" which are known, to be very conservative and reluctant to evaluate alternative materials (Delgado and Guerrero, 2006).

The lack of regulations and the inadequacy of those that exist are made worse by the lack of government initiatives and support (Nina et al., 2023). This is illustrated by a lack of fiscal incentives (El-Sawalhi and Ajwa, 2013; Hadjri et al., 2007; Kulshreshtha et al., 2020; Niroumand et al., 2013) or lack of policies to minimise the use of energy-intensive materials, such as concrete (Zami and Lee, 2011a). Government interest and support can however be a driver, as in Argentina, where different government agents are supporting the implementation of CEB due to interest in finding economic and ecological solutions to the problem of access to housing (Dorado et al., 2022).

4.4. Organisational factors

As a complement to the factors discussed previously, organisational barriers were identified throughout the literature, whether regarding the process, coordination, communication and skills and education. Indeed, barriers related to the process of creating new buildings have been notified, mostly for high-income countries. In particular, the complicated construction process, as manufacturing on-site can increase the organizational complexity and could lead to extra costs (Van der Linden et al., 2019a), especially with the need for space for storing earth in urban areas (Gasnier, 2019, p. 58). Also, the complicated design process is one consequence of the lack of codes and standards (Ben-Alon et al., 2020a) or guidance for designers (Morel et al., 2021a). Finally, earth constructions are considered time-consuming by different authors (Monzur, 2018; Zami and Lee, 2011a), although this may depend on the technique applied and dissensus have been found among authors concerning this point. Indeed, due to the "*continuous setting-up, aligning and stripping of formworks*", building with rammed earth may take longer than conventional materials and other earth construction techniques (Gallipoli et al.,

2017). On the contrary, "*Rammed earth has prefinished walls which cut construction time"* (Strazzeri and Karrech, 2023). It should however be pointed out that Strazzeri and Karrech (2023) based their study on qualitative and quantitative survey, while Gallipoli et al. (2017) did not provide scientific evidences.

Associated with processes, coordination obstacles have been reported in high-income countries only. Indeed, there is a lack of coordination and communication between stakeholders with, in particular, the need of integrating the masons in the design team and the need of warning end-users of how to maintain their earth buildings (Morel et al., 2021a). In the UK, on the one hand, there are difficulties to pool advocates forces to promote earth construction, especially since debate exists on the usefulness of hydraulic binder adjuvantation splitting professionals. On the other hand, according to the territories, the earth supply chain is disorganised (Mohammad Sharif Zami, 2021). However, there are recent initiatives, such as the PNTerre, a French earth national project supported by the government, aiming to structure future research on earth material in relation to professionals (PNTerre, 2020). Concerning the latter, a recent national organization also have been created in France, namely the "Confederation of Raw Earth Construction"[72] (CCTC) that gathers local practitioners' organizations. The CCTC may help to overcome the difficulties to access the professional network. Indeed, some training organisms struggle to find skilled professionals when, on the contrary, skilled professionals hardly convince other training organisms to create specific earth construction courses. Finally, it appears difficult for clients to access qualified professionals (Leylavergne, 2012, p. 74).

One of the most cited barriers, regardless of the socioeconomic context, is the lack of skills and education, identified as a significant barrier by many authors (El-Sawalhi and Ajwa, 2013; Hadjri et al., 2007; Kulshreshtha et al., 2020; Lu and Liu, 2013; Zami and Lee, 2011a). This goes from a general lack of knowledge within the construction industry (Williams et al., 2010) or among all the construction stakeholders (Mohammad Sharif Zami, 2021; Zami and Lee, 2011a), to a lack of specific knowledge, such as how to build earthquake-resistant earthen buildings, in seismic regions (Schroeder, 2016). A lack of technical knowledge also have been reported on the issues of the thermal behaviour of the material in Australia (Strazzeri and Karrech, 2023). Regarding the earth material, some authors describe the reason for this lack as the loss of technical know-how throughout history, due to the shift towards industrial materials (Gallipoli et al., 2017; Zupancic, 2012), which is still happening in low and middle-income countries (T.M. Marsh and Kulshreshtha, 2021). It has also the consequence of a lack

[72] Translated by the author from French to English. Original version: « Confédération de la construction en terre crue » (CCTC)

of skilled professionals (Ben-Alon et al., 2020a; El-Sawalhi and Ajwa, 2013; Spišáková and Mačková, 2015a; Strazzeri and Karrech, 2023). These two barriers are related to the lack of training courses (Hadjri et al., 2007; Niroumand et al., 2013; Zami and Lee, 2011a), which imply a resistance to change from professionals to materials beyond the scope of their background (Mohammad Sharif Zami, 2021). As an example, in Argentina, CEB is usually associated with conventional masonry construction and is thus considered as not requiring specific training, which hides the specificities of the material (Dorado et al., 2022). It is worth noting that academic courses might be too specific toward technical issues while organization or commercialization (in the case of CEB) are scarcely addressed (Dorado et al., 2022). If this is perhaps not enough, the existence of earthen architecture courses in France, India, Latin America and Germany, has recently been reported (Jörchel, 2019)[73]. In addition to professionals, end-users also lack educational features. Although sustainable solutions are well implemented by the design team, the end-users do not use them properly during the life of the building (Gasnier, 2019, p. 202).

4.5. Socio-cultural factors

Finally, the socio-cultural barriers identified concern the perception of the material, the scepticism toward its use, the lack of awareness and the resistance to change from certain organizations. Indeed, problems with the perception of the material, whether negative or misperceptions from the public have also been highlighted by many authors (Ben-Alon et al., 2020a; El-Sawalhi and Ajwa, 2013; Gado et al., 2010; Kulshreshtha et al., 2020; Spišáková and Mačková, 2015a; Mohammad Sharif Zami, 2021). Earth material is sometimes associated with “dirt” (Ben-Alon et al., 2020a), does not look “innovative” (Gado et al., 2010), or of lower quality compared to conventional constructions (Kulshreshtha et al., 2020).

Earth construction can also be perceived as unaesthetic (Hadjri et al., 2007) and must fight against false beliefs and evolving mores (Morel et al., 2021). While some people could consider earth construction as “*primitive-looking*”, others appreciate its “*simplicity and beauty*” (Sameh, 2014). Although the perception barrier has been identified in high-income and low-income countries, it still depends on the socio-economic context (T.M. Marsh and Kulshreshtha, 2021). Indeed, in high-income countries, there is a new trend for earth material, highlighted by some world-renowned architects, who promote its use for its environmental benefits and precisely for its perceived pleasant aesthetic (A. Heringer, 2017). According to some authors, the aesthetic quality is related to the material’s textural, chromatic characteristics and mass (Strazzeri and Karrech, 2023). On the contrary, the

[73] A recent report (2023), called “Terres de métiers” have been published on a diagnostic on earth construction trainings in France. It is available here: https://conf-terrecrue.org/formation-et-savoir-faire/

material is still presented, in the low-income countries literature, as having a low societal value (Gado et al., 2010; Hadjri et al., 2007; Hafez et al., 2023; Kulshreshtha et al., 2020; Monzur, 2018; Owino et al., 2014a; Pacheco-Torgal and Jalali, 2012). However, the 2022 Pritzker prize[74] has been delivered to the architect Francis Kéré, in particular for its earthen building projects, which might promote the use of earth in those countries.

The material is associated with poverty for different reasons. In the case of adjuvanted earth construction, the material is promoted by foreign agencies for poor communities and thus perceived by other communities as a material dedicated "*for the poor*" (Zami and Lee, 2011a). Generally, in low-income countries, where earth material is still very traditional, modernity and wealth are synonyms for using similar materials to conventional materials used in high-income countries (Sameh, 2014). To illustrate this argument, some authors have reported that in some communities in Egypt "*young women refuse to marry men who do not own a concrete house*", those latter being associated with high financial status (Gado et al., 2010). Besides, some authors argue that builders who have no choice but to build with earth tend to see it as a temporary option and do not maintain their earth dwellings, which negatively impacts the image of the material (Moriset et al., 2021). Interestingly, earth material can sometimes be promoted for its traditional image in low and medium-income countries for touristic purposes, such as for safari lodges (Hadjri et al., 2007). Finally, although it was specifically identified for adjuvanted earth construction, poor-quality exemplar buildings can participate in the negative perception towards earth material (Zami and Lee, 2011a). As a driver, the construction of exemplary earthen buildings and related advertisements would increase the popularity of the material among professionals and clients, which would increase the demand (M. S. Zami, 2021a).

According to some authors, one of the reasons for the wrong perception of the material is scepticism and the lack of awareness. For example, scepticism from banks and insurance agencies (Hughes E. and Elliott W. J., 2017), governments (Kulshreshtha et al., 2020), professionals in general (Zami and Lee, 2011a) and standardization bodies (Hughes E. and Elliott W. J., 2017), have been highlighted. The reason for these barriers may be the effect of a lack of awareness, that have been reported by many authors as a drawback (Ben-Alon et al., 2020a; Kulshreshtha et al., 2020; Lakys et al., 2022; Niroumand et al., 2013; Owino et al., 2014a; Spišáková and Mačková, 2015a; Zami and Lee, 2011a). A general lack of awareness or interest in sustainability is usually the cause (Niroumand et al., 2013; Zami and Lee, 2011a), whether it is a lack of awareness in general about the material (Fundi et al., 2019), or a lack of

[74] The Pritzker Prize, also known as the Pritzker Architecture Prize, is one of the most prestigious awards in the field of architecture. It is awarded annually to honour an architect or architects who have demonstrated significant contributions and achievements in the art of architecture. https://www.pritzkerprize.com/

awareness of the benefits of using earth material (Ben-Alon et al., 2020a; Mohammad Sharif Zami, 2021).

Strong resistance to change has also been identified as an obstacle to the use of earth in construction that may stem from the resistance of practitioners to the development of standards (Ben-Alon et al., 2020a). Indeed, according to Ben-Alon et al. (2020), standard development can be perceived as a threat to the "*craft-based industry*" of earth-building professionals. Resistance can also come from the construction industry itself (El-Sawalhi and Ajwa, 2013; Fundi et al., 2019). The institutional structure of the AEC sector has already been highlighted to act as a barrier to the implementation of sustainable construction, in general. The risk-averse and cost-driven approach leads to a conservative industry where innovation is highly limited (Markström et al., 2016; Park and Tucker, 2017; Zhang and Canning, 2011). The litigious culture of the AEC sector leads to discouraging practitioners to use alternative materials and techniques (Giesekam et al., 2016). The decision-making process, highly influenced by cost-effectiveness, highly fragmented and involving many different actors tends to make difficult the adoption of sustainable solutions and to have a holistic view of the asset (Giesekam et al., 2016; van Bueren and Priemus, 2002). Finally, the involvement of all the stakeholders at a very early stage in the design and implementation of sustainable solutions was notified as a key success factor (Charef et al., 2021; Häkkinen and Belloni, 2011; Zhang and Canning, 2011).

4.6. interrelationship of factors

As shown in the previous sections, many factors influence the use of earth in construction. The categorization (Technical, economic, organizational, political and socio-cultural) was required for the sake of clarity. However, every categorization has its limit. In our case, this tends to hide the interrelation of these factors between the different categories. However, no clear distinction actually exists between them.

Some authors have already highlighted this interrelation by drafting causal relations between different factors (see for example (Mohammad Sharif Zami, 2021) for barriers hindering earth construction in the UK, or (Sameh, 2014) for a systematic overview of strategies to promote earth construction in Egypt). Others have conceptualized interrelationships between different categories to highlight a vicious loop hindering earth-building materials and methods used in mainstream construction (Ben-Alon et al., 2020a) (see Figure 2.40).

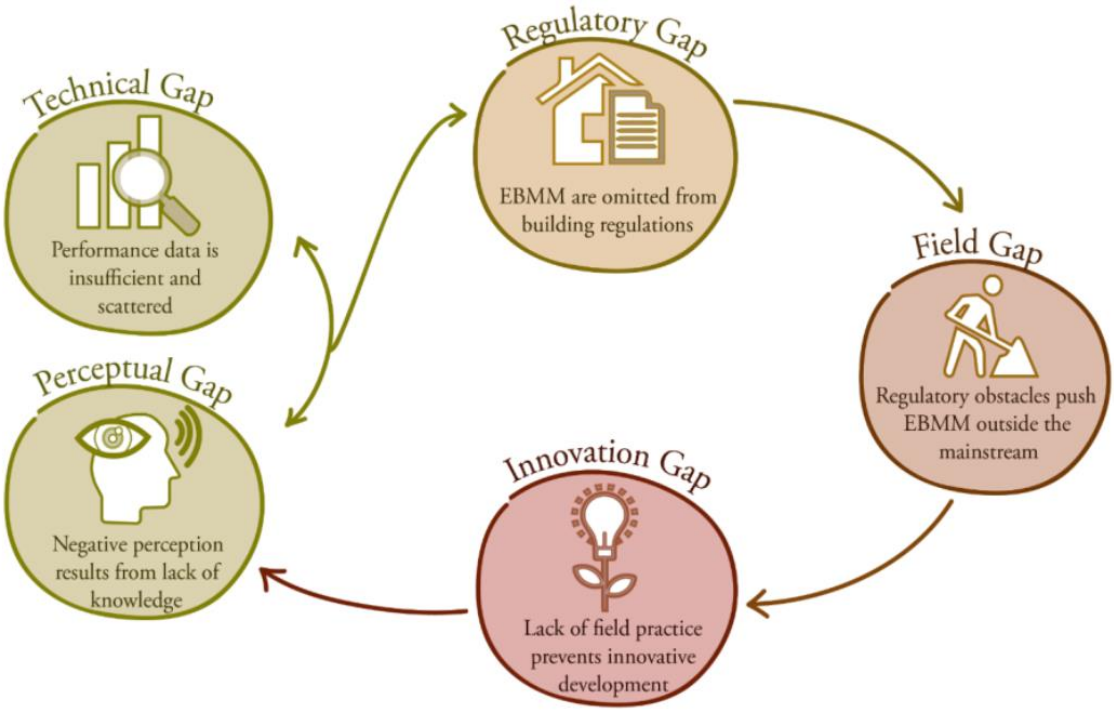


Figure 2.40: The cycle of Earth Building Materials and Methods implementation gap (source: Ben-Alon et al., 2020)

An example of the interrelation of factors hindering the use of earth in construction from the literature is provided in Figure 2.41. Indeed, the literature shows that (1) technical factors (earth variability and difficulties to relate laboratory parameters of the on-site performances of the material or the building) and (2) political factors (lack of government support, complicated process to create new regulations and lack of earth construction advocates in regulatory commissions) lead to (3) the lack of codes and standards (political factors). The latter leads to technical, organisational and political issues, and so on. The interrelation of the factors does not prevent to try to rank and prioritize those. This have been done in Egypt, for the case of CEB, based on a two stages survey among experts (twenty-two respondents for the first survey, seventeen for the second) and five interviews among survey panel. The results show that in the Egyptian context the social barriers (including client perception of the material being for the poor, poor aesthetics of CEB, prejudice towards the durability of the material) is in first priority position. Economic barriers stand in second position while technical barriers only on the third one (Hafez et al., 2023). This underscores how important it is to address other barriers than technical ones.

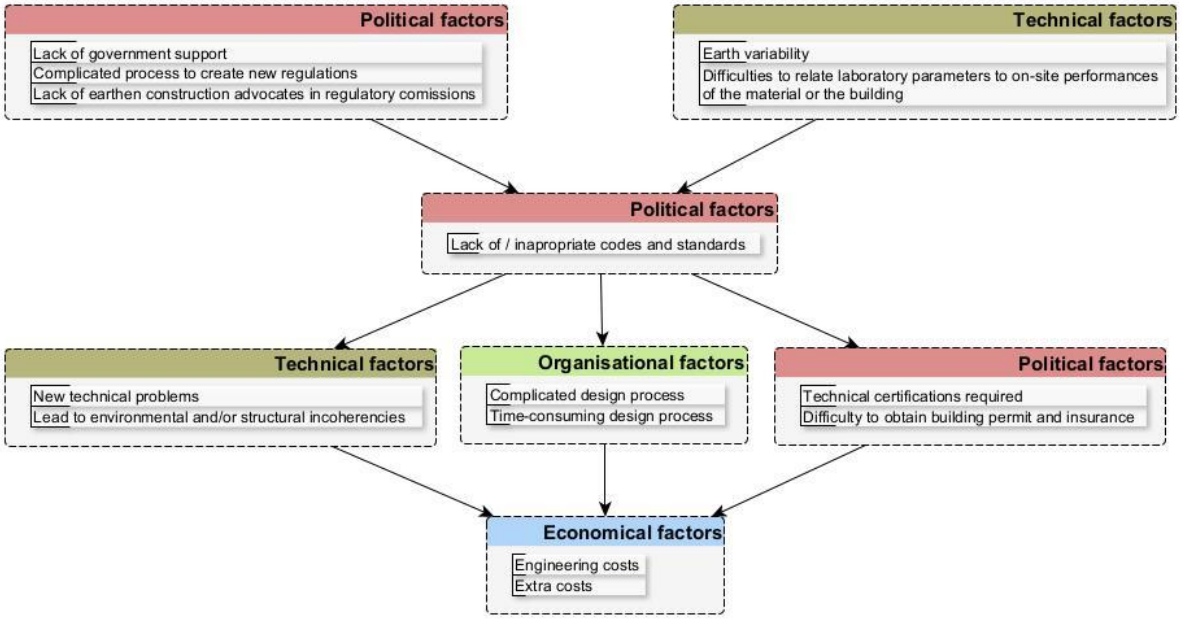


Figure 2.41: The interconnection of some barriers and drivers (source: author, published in (Pelé-Peltier et al., 2022b))

Finally, interesting for designers, another representation is drawn from the literature, connecting different factors at the design stage. This highlights the different issues on which designers can have the power of change (Figure 2.42).

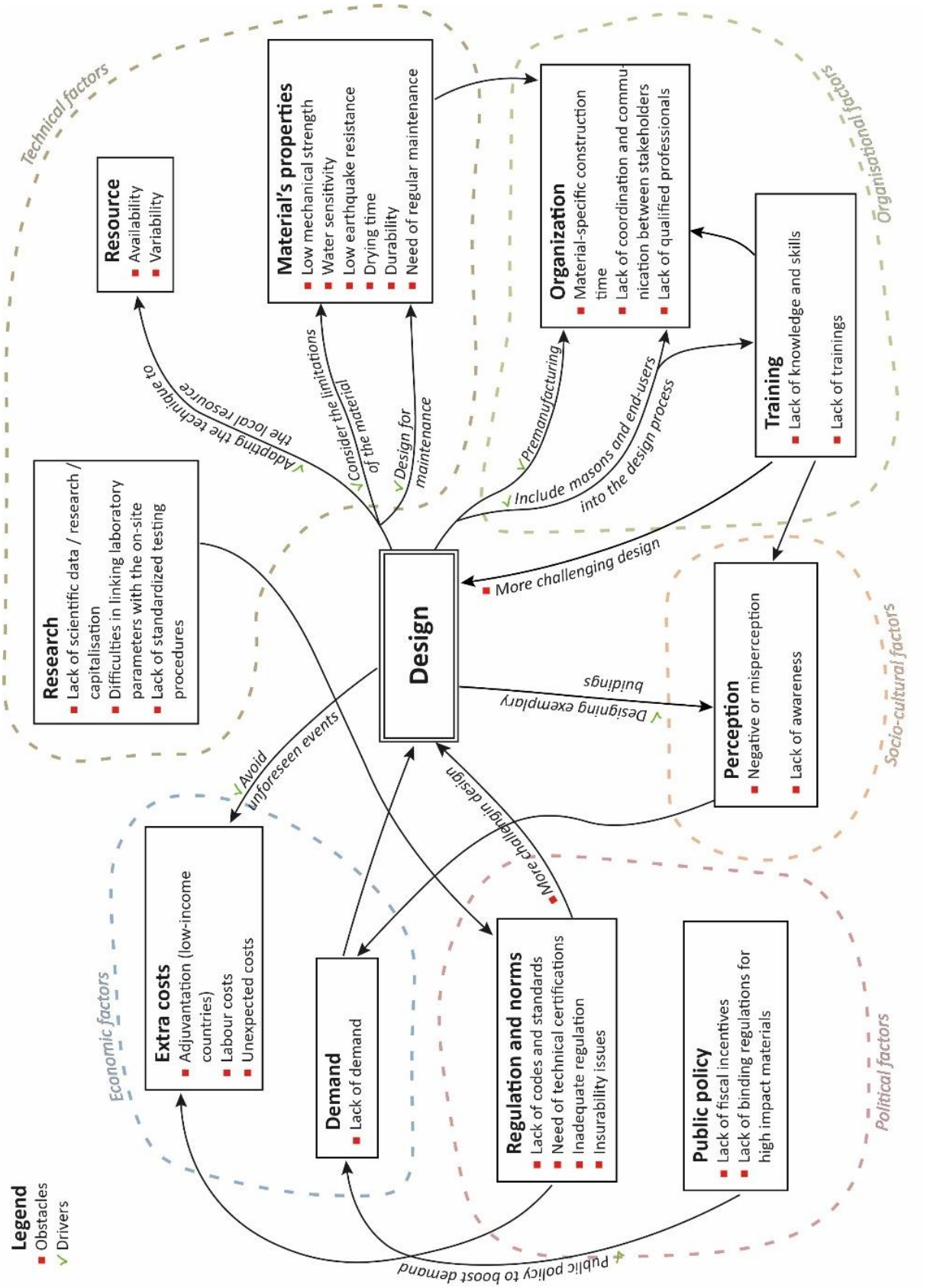


Figure 2.42: Interrelated barriers and drivers with the design of earth construction, based on the literature (Source: author)

4.7. Conclusion of the section

This section synthesized the different barriers and drivers identified in the literature, that have been categorized under technical, economic, political, organisational and socio-cutural factors. The technical barriers identified are related to the potential inadequacy of local earths or difficulties to find non-polluted earth in urban areas. However, adapting the implementation techniques have been underscored as a way to overcome these issues. The low durability, related to the low water resistance, was also identified as a main barrier according to the literature. Hence, the issue of maintenance seems complex when some authors consider the need of regular maintenance as a barrier while others highlight that earth material requires low maintenance. These differences might be explained by the variety of techniques studied in the literature, having their own issues. The influence of the technique and of adjuvantation will be discussed in section 5.1.3. Technical barriers could however be seen as limitations of the material for which a proper design is necessary to overcome those. Indeed, the case study analysis will show that for this specific context technical issues faced by designers (Chapter 5) were surmounted by adopting a proper design approach (Chapter 6).

Economic barriers identified were mostly related to extra costs, in particular in high-income countries. Indeed, in low-income countries, earth material is on the contrary seen as a low-cost material. In this case, the extra costs are coming from the use of hydraulic adjuvants. According to the literature, in high-income countries, the extra cost can be due to the lack of standards that require higher engineering costs, but also to the high labour prices related to the labour intensity of earth construction. For instance, in France, the tax system burdens more on labour than raw materials. Therefore, changing this tax system could be one way to reduce costs. A lack of demand also has been highlighted as a barrier although there is a growing interest thanks to the environmental image of the material, particularly in high-income countries. The most cited political barriers were the lack of codes and standards. Creating new standards is often seen as a driver. This point will however be further discussed in Chapter 6. Additionally, it is specified in the literature that existing regulations are sometimes inadequate for earth construction. Examples were provided with thermal regulation that are sometimes not suited to the thermal performances of earth. Concerning organisation barriers, mostly in high-income countries, a complicated design process, due to the lack of standards or guidance for designers, have been reported. However, related to the organisation of construction, some authors highlighted that as rammed earth has prefinished walls, it may cut construction time.

Finally, the negative perception of the material, scepticism toward its use, the lack of awareness or the resistance to change have been highlighted as socio-cultural barriers. However, this depend to the economic context where in high-income countries, a new trend seems observable, while in low-income

countries, the material is still associated with poverty. The distinct categories chosen should however not hide that all of these barriers and drivers are interconnected. Meanwhile, categorizing allows to prioritize the actions to lead. Interestingly, recent studies have concluded, in the context of CEB in Egypt, that socio-cultural barriers are the top priority to address.

Finally, while discussing all the barriers and drivers, it appears that these are dependent of different parameters including the geographical and socio-economic context, the political context, the specific techniques considered but also the ways barriers are studied. This will be the topic of the next section.

5. Ways of studying barriers: toward a conceptual framework

This section will be dedicated to introducing the conceptual framework developed from the literature to address the research question: “What are the barriers to the use of earth in construction?”. Throughout the literature, two main Research Approaches (RA1 and RA2) were identified and will be described here. Besides, some limitations and parameters to consider, while studying barriers, also have been identified. In particular, research approach 2 (RA2) has limitations primarily due to a lack of situating. Therefore, a conceptual framework will be proposed to enhance RA2 and address the identified weaknesses. This conceptual framework will then be utilized as the research approach for the subsequent chapters, particularly for the case study analysis. This will allow to position this current PhD thesis within the literature. The discussion around these researches approaches and the proposed one does not invalidate the results and discussion of the previous section. Indeed, it only helps to situate, from situated knowledges perspectives, the results obtained in the literature. However, by proposing a new research approach, this section aims to reflect how to better situate research on barriers and drivers.

5.1. Two main research approaches identified in the literature

The two main research approaches (RA1 and RA2) identified in the literature will be described in this section. It should be noted that the research approaches that will be described have been conceptualized by the author because none of the literature explicitly refers to any of these research approaches. Besides, although these two approaches will be presented distinctly, some studies combine both. As an example, in Ben-Alon's (2020) PhD thesis, both research approaches were identified, the RA2 was used for her first general investigation of barriers, and the RA1 was used for her investigation focusing on the perception of earth construction among experts and homeowners.

5.1.1. Barriers, obstacles, drivers…: some definitions

First of all, it is important to define the terms barriers and drivers as it will help to define the research approaches.

Different wordings were used in the literature that can refer to barriers, for instance, "*challenges that hinder*" (Mohamed Gomaa et al., 2022), similarly "*problems that hinder*" (Dorado et al., 2022), "*barriers*" (Ben-Alon et al., 2020a; Mohammad Sharif Zami, 2021), "*obstacles*" (Cataldo-Born et al., 2016; Morel et al., 2021a; Niroumand et al., 2013), "*factors limiting*" (Kulshreshtha et al., 2020) or "*inhibitors*" (Zami and Lee, 2011a). Referring to the Cambridge dictionary, the most relevant definitions, considering the context of the study, of these terms are reported in the following table:

Table 2.11: definition of common terms used in the literature studied obtained from Cambridge Dictionary

Hinder	To limit the ability of someone to do something, or to limit the development of something
Barrier	Anything used or acting to block someone from going somewhere or from doing something, or to block something from happening. Or Something that prevents something else from happening or makes it more difficult.
Obstacle	Something that blocks you so that movement, going forward, or action is prevented or made more difficult Or Something that blocks your way so that movement or progress is prevented or made more difficult
inhibitor	Something that stops or slows down a process

Although differences can be noted between these definitions, they have in common to describe something that creates difficulties in a movement or process or to achieve something (objective). On the contrary, a driver can thus be understood as something helping that movement or process to achieve the objective. From these definitions, two research approaches can be conceptualized from the literature.

5.1.2. First research approach: between stakeholders and the use of an object (RA1)

The first research approach that can be found in the literature attempting to address the research question can be understood as: the study of the things that create difficulties in the movement of

stakeholders toward the adoption of something or the use of an object (Figure 2.43). An enlightening example of such an approach is the study of Shahabadi et al. (2019), where the authors investigated "*what is the relationship of economic and environmental factors with the acceptance of newly built earthen houses in the city of Yazd*" (Zare Shahabadi et al., 2019), studying a specific population composed of "*young educated couples*". In this type of study, for which social science is useful, the focus is on understanding "*barriers*" and "*drivers*", as defined above, between stakeholders and the adoption, or use, of an object[75] (in our case, the object can refer to earth material, earth techniques, …). In this concept, stakeholders are central to the study and investigations of different stakeholder's perspectives, as in the study of Lakys et al. (2022) are interesting.

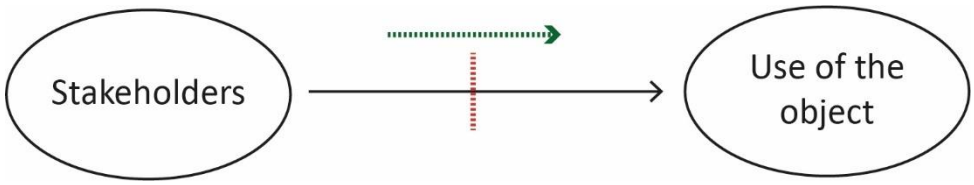


Figure 2.43: Schematic representation of the first concept identified through the literature, barriers are represented in red while drivers are represented in green

5.1.3. Second research approach (RA2): between object and objective

The second research approach (Figure 2.44) that can be drawn from the literature could be described as the study of the things that create difficulties in the movement of an object to achieve an objective. In our case, the object can be various, including the field of "earth construction" or specific techniques, such as CEB, and the study focuses on the "development" (Morel et al., 2021a) toward an objective that is not always defined in the literature.

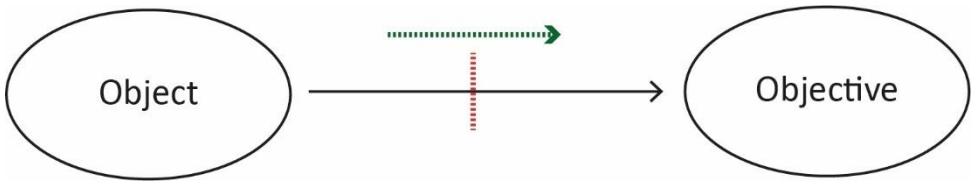


Figure 2.44: Schematic representation of the second concept identified through the literature, barriers are represented in red while drivers are represented in green

This research approach is the most represented in the literature (group 1) as represented in Figure 2.45.

[75] Object here is chosen in a broad sense: it can also refer to a behaviour

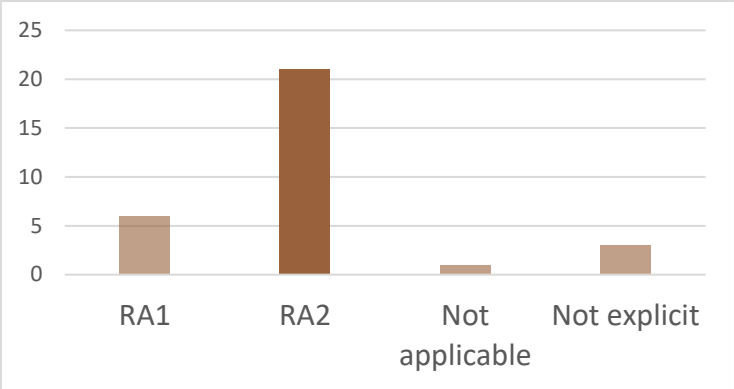


Figure 2.45: Numbers of papers (among group 1) per research approaches (RA).

There is a notion of the scale of study in what is considered here as "the object". Different scales can be found in the literature, from the buildings case study analysis to the entire field of earth construction. Then, The objective can be to integrate the object "*earth construction*" into "*mainstream construction*" (Ben-Alon et al., 2020a), although mainstream construction could have different significations. The objective can also refer to a "*greater dynamization*" of the field of earth construction (Dorado et al., 2022), or again "*scaling up*", in the case of specific techniques such as 3D printing, to an "*industrial scale*" (Mohamed Gomaa et al., 2022). See Table 2.12 for example of object and objective for some of the papers using RA2.

Table 2.12: Example of object and objective for some studies using RA2 to investigate barriers and drivers for the use of earth in construction

Authors	Object	Objective
Hafez et al., 2023	Compressed Earth Blocks construction	Integration in the construction sector
Lakys et al., 2022	Compressed Earth Blocks construction	Integration in the construction sector
Strazzeri and Karrech, 2023	Rammed Earth Technology	Integration in the construction sector
Zami, 2021	Earth construction	Integration in the construction sector
Morel et al., 2021	Earth construction	Development of earthen architecture from circular economy perspective

Studies addressing the research question through this approach tend to imply unique perspectives of development (objective) of a unique object, namely earth construction or earth architecture, which is untrue. Indeed, there are many ways of "*developing*" what we call earth architecture, the latter being plural as well (See Pelé-Peltier and Goizauskas (2023) for an attempt to contrast ways of building with earth according to circular economy principles). To illustrate, Niroumand et al. (2013) refer to "*obstacles […] in the development of the architecture of earth and earth's buildings*" without specifically describing what development would mean. Similarly, Morel et al. (2021) have studied "*the current obstacles against the development of earthen architecture*". This study, however, is the first to situate itself in a circular economy context.

These studies, by not defining what development might mean, suggest that there is only one way of development, although this is not consensual among professionals. Indeed, as Villain (2020) showed in his PhD, in the French context, that the perspectives of development are different according to the political thinking of the different stakeholders. He has identified five groups of professionals: (i) industrial producers wanting "earth construction" to satisfy economic constraints of mainstream construction; (ii) professionals that are balancing between "industrial logic" and "craftsmen logic"; (iii) professionals wanting to change the social structure by, for example, giving priority to labour against technical assets; (iv) and more recently professionals tending toward a symbolic revolution in the field of conventional constructions, (v) or on the contrary a conservative revolution in the field of construction (Villain, 2020, p. 212). Therefore, the selected literature, being in RA2, can be criticized similarly to the critique established by Villain (2020) about reports published in France addressing the issue of "*barriers to the development of earth construction*":

> *"[These studies] simply subscribe to the implicit problem of the economic field by* ***measuring the existing gap between the state of the field of earth construction and that of the construction field, with their respective dominant vision principles****. What is thus considered as* ***"obstacles" to earth construction in France is the expression of a ratification of the dominant vision principle in the construction field by a part of the professionals****."*[76] *(Villain, 2020, p. 403)*

[76] Translated from French to English by the author. Original version: *« [Ces études] ne font que souscrire à la problématique implicite du champ économique en mesurant le décalage existant entre l'état du champ de la construction en terre crue et celui du champ de la construction, avec leur principe de vision dominant respectif. Ce qui est ainsi considéré comme étant des « obstacles » à la construction en terre crue en France est l'expression d'une ratification du principe de vision dominant du champ de la construction d'une partie des professionnels.* »

In other words, these studies tend to be situated into dominant visions of both earth construction and construction field, without making visible this situation, which constitutes a bias or a lack of situating. This is one principle of situated knowledges theory: any knowledge, here scientific studies, is situated, here in the dominant vision of construction and earth construction (Figure 2.46). And therefore, for more rigorous research about barriers and drivers to the use of earth in construction, these visions should be pointed out.

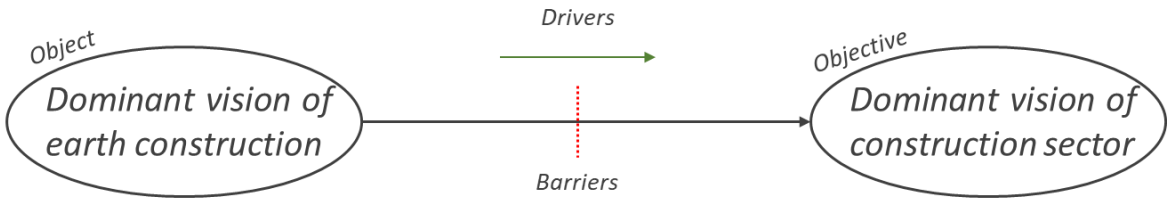


Figure 2.46: A schematic representation of what tend to investigate studies using RA2 without explicitly notifying it.

Using this research approach, barriers will depend on the definition of the object. Particularly when specific techniques or adjuvantation are considered. For instance, barriers reported for compressed earth blocks (CEB), that might not apply to other techniques, include the problem of transportation and the obligation to minimize the distances due to the weight of CEB. Additionally, excessive breakage can appear during transportation, thus affecting the image of the material (Dorado et al., 2022). Another example is the adjuvantation that has an impact on different factors, such as durability, cost, or acceptability. Besides creating opportunities, it can also create new drawbacks, such as the problem of finding curing space in controlled hygrothermal conditions for adjuvanted CEB (Dorado et al., 2022). On the contrary, stabilisation is sometimes required to convince clients and insurance offices to build with earth (Marsh et al., 2020). Therefore, a clear distinction between adjuvanted and non-adjuvanted material should be made for further studies on barriers and drivers, which was not always done in the papers studied (see for example (Adeniyi and Mohamed, 2019; Hadjri et al., 2007; Niroumand et al., 2013)).

Similarly, the perspectives of development considered will influence the study of barriers, but other parameters need to be investigated, which will be the purpose of the next section.

5.2. Limitations and parameters to account for while studying barriers

Besides the description of the object and the objective for the study of the barriers, it is necessary to consider the context of the study, including the geographical, socio-economic and political (or normative) contexts, because such parameters have influences on barriers.

5.2.1. Geographical and socio-economic context

In this section, we will examine the differences in factors affecting the use of earth between high-income and low-income countries. Significant differences and similarities in the barriers cited can be observed (Figure 2.47). Indeed, technical barriers seem preponderant in low-income countries, particularly barriers related to material properties, whereas they are secondary in high-income countries. Similarly, political and organisational-related barriers are cited more in high-income country's papers, than in low-income ones. However, some barriers are consistently cited in both categories, such as those related to "Skills & Education", "Design, Construction and Maintenance", "cost" or "Perception".

Additionnaly to the socio-economic context, it is important to consider the climatic conditions where the studies have been investigated. Indeed, some papers, particularly those concerning low-income countries, have studied barriers to earth construction in flooding areas, such as Bangladesh (Monzur, 2018), or subjected to very strong rains, such as in India (Kulshreshtha et al., 2020). However, earth material is known to be very sensitive to water (Bui et al., 2014a; Champiré et al., 2016), and thus the climatic conditions have a major impact on the material. This might be one of the reasons for the preponderant citations of barriers related to "Material properties" in papers associated with low-income countries.

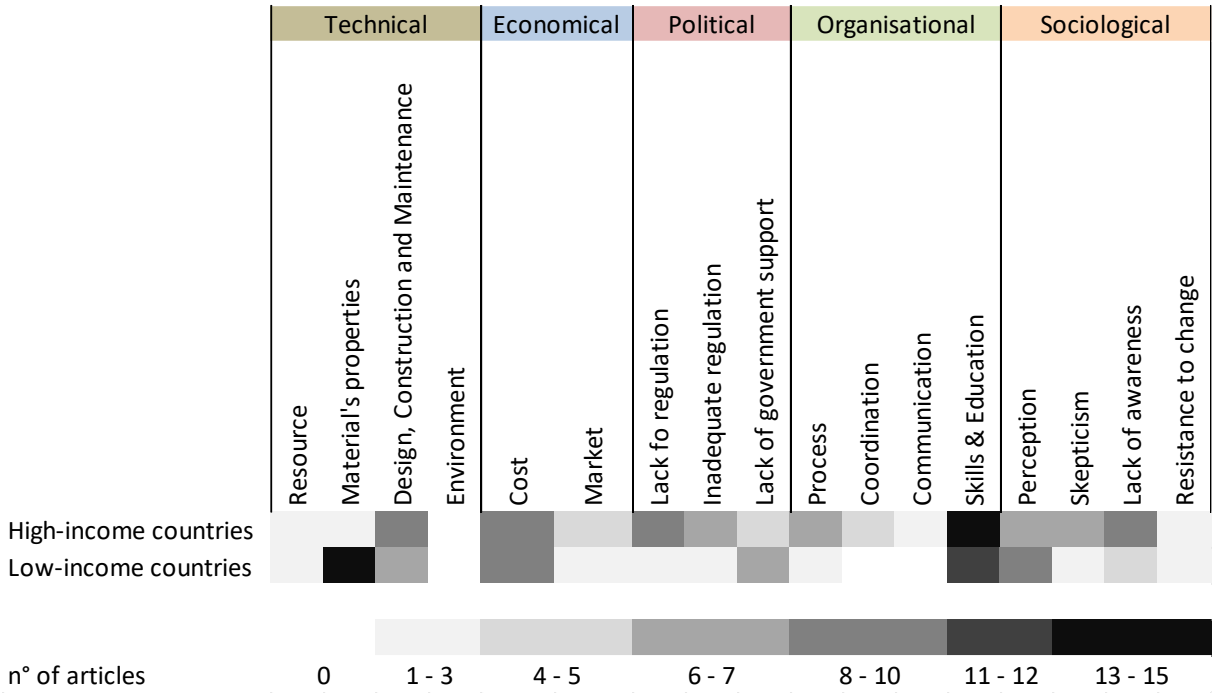


Figure 2.47: Type of barriers most cited for high-income countries and low-income countries, the darker the cell, the more the barrier is cited.

This part highlights that, while studying factors affecting the use of earth, situating the study in the socio-economic context is major. This was generally done in papers studied in the literature review.

Other non-exhaustive factors that could be included in the description of the context in which the studies are carried out could be the type of market studied (informal vs. formal construction, private vs. public) or the scale of the study (field, project scale, product, sector, …).

5.2.2. Political context

Along with the geographical and socio-economic context, and closely related to it, the political context (i.e. regulative and normative) should also be considered while studying barriers, as different political contexts will have different implications and impacts on barriers and drivers.

To illustrate the argument, a study has shown the constraints toward bio-based materials implied by the French normative system by comparing it to other countries in Europe and describing three types of normative systems. The first describes the French system (but also found in Italy, Sweden and Spain), while the second is found in Finland, Denmark, Ireland or Switzerland and the third in the UK:

> *"(1) The so-called 'all-insurance' system, of which France is the most accomplished example, with a legal requirement for builders to take out insurance.*
>
> *(2) The "all-contractual" system, which does not require insurance, establishes contractual commitments between individuals and constructors, falling under the civil code provisions applicable to legal entities or individuals.*
>
> *(3) The system known as 'contractual,' with no insurance obligation but very frequent use of mediation organizations between individuals and constructors, outside the compensation process or as a last resort for compensation."*[77]
>
> *(GT biosourcés action 18c, 2012)*

Additionally, Tayyibi et al. (2016), by comparing six international codes and regulations, conclude that "each code or regulation is influenced by the specific country's context" (Tayyibi et al., 2016). They illustrate this conclusion with two countries having different approaches: India and Morocco. The first targets industrialization, while the second is more conservative, according to the authors but without

[77] Translated by the author from French to English. Original version: *« (1) Le système dit de type « tout assurantiel » dont la France est l'exemple le plus abouti, avec l'obligation légale de contracter une assurance pour les constructeurs. (2) Le système dit de type « tout contractuel » avec absence d'obligation d'assurance établissant entre particuliers et constructeurs des engagements relevant du code civil entre les personnes morales ou physiques. (2) Le système dit de type « contractuel » avec absence d'obligation d'assurance mais un usage très fréquent d'organismes de médiation entre particuliers et constructeurs hors processus d'indemnisation ou avec indemnisation en dernier recours* »

further describing what a vision of industrialization would mean compared to a conservative vision. Therefore, specifying the normative context is required.

Besides, barriers and drivers might depend on the level, or number, of normalisation and regulation, the way those norms were created, etc…

5.3. A new conceptual framework as a research approach for investigating barriers and drivers from situated knowledges perspective

Finally, based on previous comments and the second research approach (RA2) described before, it is possible to propose a new conceptual framework useful for this PhD thesis. This will help to frame the analysis and contextually define what barriers and drivers mean in this thesis (Chapter 4).

It is worth noting that the aim of this section is not to criticise the quality of the results presented through the studied above cited, but to highlight some shortcuts that are made while studying barriers to the use of earth in construction. To improve the rigour of such a study, it is important for researchers to describe or at least highlight “the object”, “the objective”, the stakeholders involved or perspectives, but also the context (i.e. geographical, socio-economic, political), as a mean to situate the research. Figure 2.48 presents a scheme of the adapted research approach for the thesis.

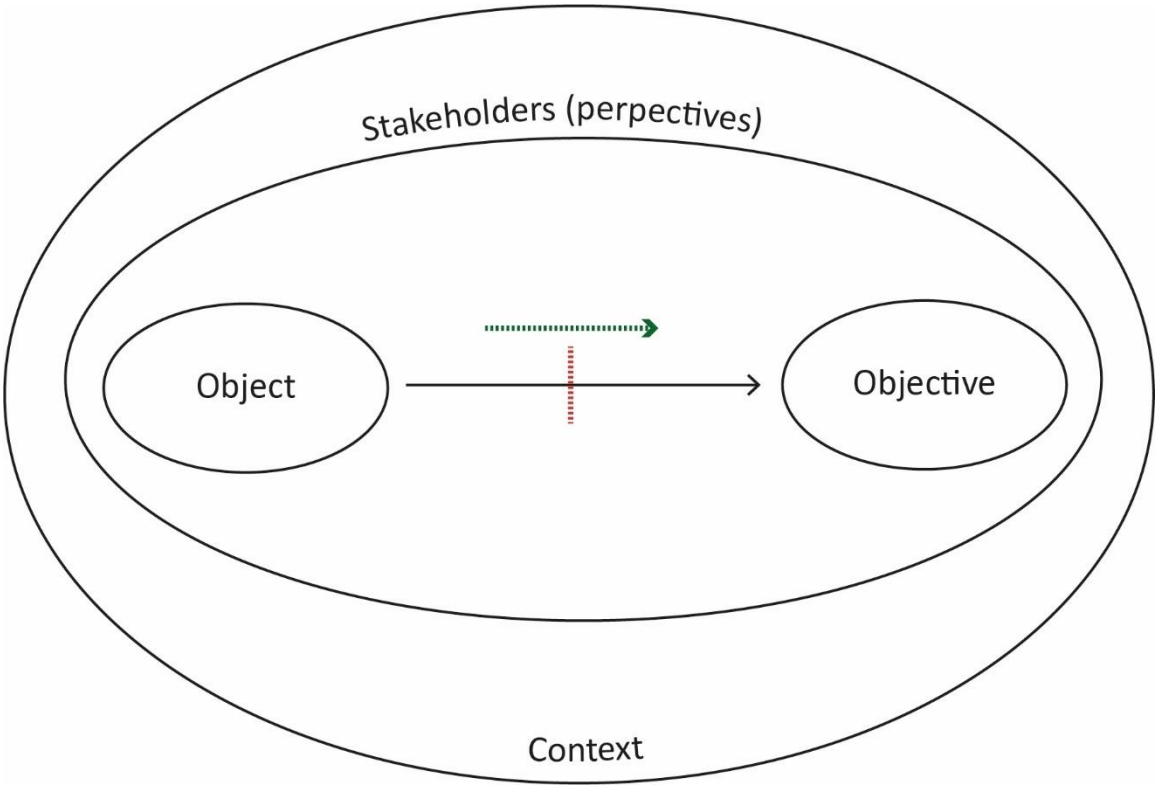


Figure 2.48: Schematic representation of the conceptual framework used as a research approach for this study (improved RA2). This will be adapted considering the method choice. barriers are represented in red while drivers are represented in green.

The object could refer to the type of techniques studied (e.g. rammed earth (Zawistowski et al., 2020), cob, adobe (Adeniyi and Mohamed, 2019), …), the type of material (adjuvanted (Mohamed Gomaa et al., 2022) or not (Morel et al., 2021a)), but also the scale of the study (Is it the study of product development? (Lakys et al., 2022), is it a case study of a project or multiple projects? (Van der Linden et al., 2019a) etc…).

Regarding the objective, I believe that it is more difficult to define. It might not be the role of the researcher to make assumptions about development prospects. Or at least if assumptions are made, they should be presented as such. For instance, researchers could situate themselves in one of the groups developed by Villain (2020) and already described in section 5.1.3. Some avenues for addressing this issue could be, for instance: (1) to carry out a prospective study by describing what could be, according to professionals, the development of earth constructions (including the distinction between types and categories of professionals)[78]; or (2) at least, integrate questions on what respondents think

[78] In France, the socio-cultural axis of the national earth project has proposed a research project on the imaginaries surrounding raw earth as a building material.

this development could be. Spotlighting these different ways of development (more generally "the objective") is necessary to situate research.

Then, a description of the context, including some insights on the geographical, socio-economic, and political context seems crucial when studying barriers.

Finally, to some extent, insights might be provided on the perspectives of different stakeholders some types of stakeholders might see specific issues as barriers while others might disagree.

The description of the context, stakeholders' perspectives, object and objective, although necessary to achieve a rigorous study of barriers, might be more or less difficult according to the scale of the study. Difficulties can be encountered in particular when studying an entire sector (e.g. earth construction). One of the purposes of this study is to highlight the interest in reducing the scale and focusing on a single case study analysis in the application of this framework. Indeed, Chapter 3 will describe the methodological choice for the thesis of a single case study, and Chapter 4 will adapt the conceptual framework for this type of study.

5.4. Conclusion of the section

Two research approaches (RA) to investigate the research question of "*What are the barriers to the use of earth in construction*" were identified[79] in the literature: (RA1) The first investigates the barriers between specific stakeholders (for example clients) and the use of earth in construction; (RA2) the second examines the barriers between what has been called an "object" to achieve an "objective". For instance, the "object" can be earth construction field to entering mainstream construction, the latter being therefore the "objective". In the second approach (that have been chosen for this thesis), a lack of situating, representing a lack of rigour, has been identified. Indeed, these studies tend to be situated into dominant visions of both earth construction and mainstream construction, without making visible this situation. For instance, studies investigating the "*barriers to the development of earth construction*", actually examines the barriers between a dominant vision of "*earth construction*" to integrate a dominant vision of "*mainstream construction*", without specifying it. This might hide other possibilities or potentialities, notably according to the context. This is a typical issue raised by situated knowledges theory. Therefore, when using this approach there is a need to situate the research, in our case by specifying what is considered as the object and objective. From this critique a new conceptual framework is proposed for further research. This conceptual framework will be implemented for the case study analysis and could help to tend to situated research.

[79] It should be noted that these approaches have been identified by the author of this thesis and are not specified in the literature.

Finally, thanks to the analysis of the literature and situated knowledges theory, it was possible to identify another lack of situating in articles that introduce their research questions using barriers without scientific evidence. This will now be discussed.

6. Barriers used in literature: express specific visions of earth construction?

This section considers papers that do not investigate barriers as an aim and research question associated, but only mention barriers as a justification for their research question. As introduced in the general introduction of the thesis, some of these articles, often with technical aims, do not provide scientific evidence or justifications (e.g. scientific references) to support the argument of pointing out some barriers. This represents a lack of rigour but also raises concerns on the degree of validity of the barriers that are put forward (are there valid whatever the context? Whatever the situation? Or not. Or on contrary, are they valid under a specific scope?... etc). Table 2.13 gathers some of these recent papers after a quick review on Scopus using "*earth construction"* as a keyword.

Table 2.13: Table gathering recently published articles incorporating barriers to justify their research aim

Author	Themes	Date	Barriers identified	Quotation
K. Vikas	Stabilisation	2023	Low durability	"The main drawback of this technique is its lower durability"
B. Sen	Stabilisation	2022	Seismic vulnerability	"Unreinforced earthen houses offer manifold environmental and economic advantages. However, such houses are inadmissible in today's era due to their poor performance during earthquakes"
A. Cuccurullo et al.	Stabilisation	2022	High vulnerability to water erosion	"Raw (unfired) earth represents a sustainable and efficient alternative to traditional construction materials but its dissemination into building practice has been hindered by a relatively high vulnerability to water erosion."
F. Avila et al.	Stabilisation	2022	Properties too low to reach minimum required performances by standards	"The use of rammed earth in modern construction, however, often requires an improvement of its properties in order to reach the performance levels fixed by the diverse national and international standards"
Medvey and Dobszay	Stabilisation	2020	Low durability	"It has become general practice to stabilize earthen materials with chemical binders since one of their main weaknesses is their lack of durability"

M. Kohandelnia et al.	Novel techniques	2023	Rammed earth is time-consuming, labour-intensive, energy consuming	"The rammed earth (RE) method, as a common earthen construction, consists in casting the material layer-by-layer, which is time-consuming, labour-intensive, and energy-consuming. Designing self-consolidating earth concrete (SCEC) can speed up the construction process and overcome the disadvantages of conventional RE and enhance its performance."
M. Kohandelnia et al.	Novel techniques	2022	RE Time-consuming and labour-intensive	"RE construction is a very time-consuming and labour-intensive process due to the consolidation required to achieve the targeted performance."
A. Birga-Sa et al.	Novel techniques	2022	Limitations are not pointed out	"Construction with interlocking compressed earth blocks (iCEBs) is a recently developed technique, put in evidence in the last few decades, for overcoming many earth construction limitations."
A. Perrot et al.	Novel techniques (3D printing)	2018	Low production rate	"Due to its low environmental impact, earth construction has received much consideration in recent years. Nevertheless, its development remains limited due to low production rate."
M. Schweiker et al.	Novel techniques (3D printing)	2021	Lack of knowledge of materials properties, lack of standards for modern methods, Lack of professionals	"Research gaps regarding physical properties, missing standardisation concerning building law and modern construction methods, and a limited number of manufacturers are hindering a wide application of earthen construction worldwide"
Ana Mafalda MATOS et al.	Novel techniques	2022	Low industrial level, variable final product properties	"The low industrialisation level and variable final product properties are the main barriers to wider use of earth material"
Ola Nashed Kabalan et al	Novel techniquecs (3D printing)	2022	Sensitivity to water, low mechanical resistance, cracks in the drying phase during shrinkage	"raw earth as construction material […] is still considered as a non-standard building material due to its sensitivity to water, low mechanical resistance and the high tendency to crack during the drying phase as a result of shrinkage phenomenon"
Pinel et al.	Poured earth	2017	Low production rate	“Currently the development of earthen construction on a large scale is limited by economical and technical difficulties. Even if there are numerous traditional ways of building with earth, they generally involve the compaction of a plastic or moist mixture. Solidification is then achieved by drying. The low productivity and therefore high cost of such building methods are the main drawbacks. Another major issue is the large diversity of materials used, which makes standardisation difficult.”

What is notable from this table is that articles generally arguing for the low durability of the earth material acting as a barrier to its use are investigating the use of *stabilisers* (adjuvants) to decrease the water sensitivity of the material. Moreover, this low durability is spotlighted as a main barrier: "The *main drawback of this technique is its lower durability*" (Vikas et al., 2023); the "*dissemination into building practice*" of earth material *"has been hindered by a relatively high vulnerability to water erosion*" (Cuccurullo et al., 2022); or even adjuvantation with chemical binders is described as having become "*a general practice […], since one of their main weaknesses is their lack of durability"* (Medvey and Dobszay, 2020). However, it has been shown in this chapter that *(1)* the *"low durability"* of the material was mainly underlined as a barrier in low-income countries according to the literature, and is therefore context-specific, in particular considering the local weather conditions. And *(2)* the technical barriers (among which the low durability is part of) are only a small part of the barriers identified in the literature review. Therefore, it is difficult to accept the assertion that it would be "*the main barrier"* to the use of earth in construction. Then, the suggestion that low durability would mean the necessity of using adjuvants (which is implicitly argued in those articles) is also open to discussion. While durability in earthen structures is largely linked to water resistance, it is worth noting that many, if not all, risks associated with the material's sensitivity to water can be mitigated through appropriate architectural design (Beckett et al., 2020)[80]. Besides, Beckett et al. (2020) highlighted that *(1)* the belief that higher strengths lead to increased durability emphasizes and favours adjuvanted construction methods and *(2)* the perception of conventional building materials (such as concrete, fired bricks or steel) as being 'durable' in term of their design lifespan "*has reduced the perceived importance of regular maintenance or durability assessment*" (Beckett et al., 2020). Indeed, the notion of maintenance could be a constitutive part of durability, particularly in the case of earth construction. Some authors, from a sociological perspective, have studied the issue of maintenance toward objects in general (Denis and Pontille, 2022), but this topic could be the subject of further research in earth construction. Finally, from situated knowledges perspective, it is crucial to note that the assumptions "*the low durability of earth material act as a main barrier to its wider adoption*" and "*the low durability would necessitate to use hydraulic adjuvants*" both hide other opportunities of research, involving other fields, as maintenance.

Another point that can be raised from Table 2.13 is the arguments involved to justify research on novel earth construction techniques: For instance, rammed earth is depicted as time-consuming and labour-

[80] Beckett et al. (2020) conducted a comprehensive review on 59 articles discussing the results of 118 durability assessments for 686 different earthen materials. The study identified twelve assessment methodology categories and thoroughly examined and evaluated each category based on the materials examined, their performance, and, when possible, how degradation correlated with observed in-situ conditions. Finally, the authors proposed a framework to assess material durability providing examples, based on different scenarios, of its use.

intensive to promote "*Self-consolidating earth concrete*" (Kohandelnia et al., 2023); similarly articles investigating 3D printing with earth argue that the *development* of earth construction "*remains limited due to low production rate*" (Perrot et al., 2018). Focusing on the latter, in the introduction, but still with no scientific evidence, Perrot et al. (2018) write the following: "*The development of earthen construction is still limited because of the price, insurability difficulties and bad durability due to high water sensitivity*" (Perrot et al., 2018). However, such an assertion is questionable for at least three reasons: *(1)* as explained in the section 5.1.3, the potential "*barriers*" to a "*development*" of earth construction imply implicitly considering a unique possibility of development of a unique earth construction field, while both can be plural (see for example (Pelé-Peltier and Goizauskas, Under review) for different development perspectives in a context of circular economy); *(2)* As described in section 4, there are many different, and interconnected, barriers to the use of earth in construction that cannot be reduced only to a problem of *"price, insurability difficulties and bad durability"*, in particular when *(3)* these barriers are context-specific. For instance, the literature review highlighted that, while the cost might be seen as a barrier in high-income countries, due to high labour costs in particular, in low-income countries on the contrary, earth material is often described as low-cost[81]. Once again, this is an example of a bias of situated study that does not recognize itself. Indeed, for instance, assuming that "*the development of earthen construction is still limited because of the price"*, without contextualizing in high-income countries (where it is a defendable opinion) might be seen as the expression of a dominant vision of construction and hiding the specific situations of low-income countries that are less concerned about the price of the material.

Therefore, the literature review helped to identify a bias in some research, particularly in their introductions and abstracts. Thus, one should be aware that the critics are not based on the quality of the science carried among this research for which I would not have the knowledge and skills to criticise.

However, the critics point out a lack of situating of such assertion that bring the bias. Indeed, barriers or obstacles can here be understood as defined by Victor Villain in his thesis:

> *"What are thus considered to be "obstacles" to raw earth construction in France are the expression of a ratification of the **dominant vision** of the construction field on the part of some professionals."*[82] *(Villain, 2020, p. 403)*

The following example will further illustrate the argument. When researchers argue that earth construction cannot be widely accepted due to low production rate, they might carry a *dominant vision*

[81] And the affordability for low-income countries of 3D printing technologies can definitely be questioned.

[82] Translated from French to English by the author. Original version; « *Ce qui est ainsi considéré comme étant des « obstacles » à la construction en terre crue en France est l'expression d'une ratification du principe de vision dominant du champ de la construction d'une partie des professionnels.* »

of construction: they think that it is a necessity for earth construction to increase its productivity (in other words, must be fully industrialised) to be more widely used in mainstream construction. In that sense, increasing the production rate would be at worst the only way, at least a condition, to facilitate the use of earth in construction. Therefore, those researchers can be situated in the first category proposed by Villain (2020) (i.e. wanting "earth construction" to satisfy the economic constraints of mainstream construction). This position can be held as long as it is pointed out, which is not the case in the literature reviewed. On the contrary, the fact of not making explicit this position (and therefore not situating this knowledge) might have the effect of hiding other potential visions and concealing the situated dominant vision (considering that the increase in the rate of production is a necessity for instance). Indeed, there is a diversity of contexts, barriers, and paths as well as of *vision* of what the development of earth construction should be. Figure 2.49 conceptually represents this issue with the example of the vision of a need to increase the production rate.

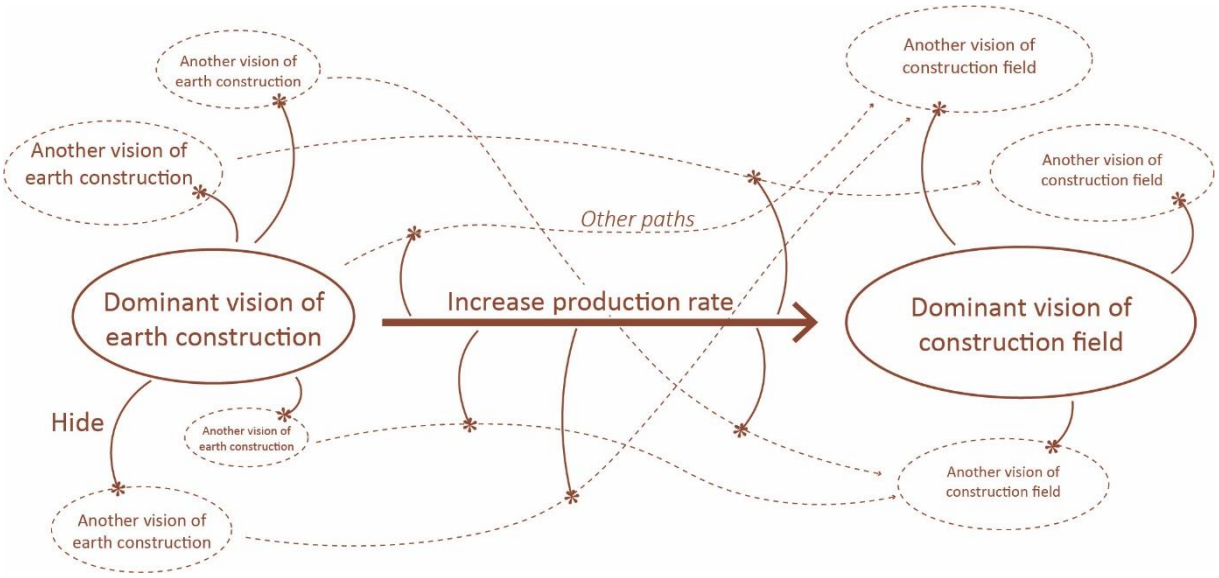


Figure 2.49: Schematic representation of dominant visions of earth construction, barriers and construction field hiding other potential visions

Therefore, through a few examples, we can understand that the mobilisation of hypothetical *barriers* to the use of earth in construction might convey a bias of dominant situated vision that the theory of situated knowledges of Haraway (1988) can help to identify and therefore overcome. Indeed, assuming that the knowledge and its construction are situated helps to highlight that other ways are possible. This is why the rest of this thesis will aim to situate the different research work carried out, as much as possible. Finally, this thesis does not aim at describing what are the dominant visions and what could be the others. Further research could however investigate this issue.

7. Conclusion

In this chapter, comprehensive insights have been provided on what the literature says about barriers and drivers to the use of earth in construction. A three-step methodology (exploration, systematic and snowballing search) was carried out for data collection. 72 documents (including peer-reviewed journal articles, conference papers, master's thesis and book chapter), along with 5 theses, were therefore selected. The quality of these documents has been discussed, highlighting the lack of well-structured scientific research on the subject, which represent a research gap addressed by this thesis. From the literature, barriers and drivers have been classified and described in five categories: technical (material resource, material's properties and design, construction, and maintenance phases); economic (cost, market); political (regulation, standards, government support); organisational (processes, coordination, skills and education) and socio-cultural (perception, awareness). These factors are interconnected and depend on the context and the type of material considered, as well as the stakeholders involved.

Two research approaches to studying barriers and drivers have been identified and conceptualised for this chapter. The first approach (RA1) can be understood as studies of the things that create difficulties in the movement of stakeholders toward the adoption of something or the use of an object. The second approach (RA2) could be described as the study of the things that create difficulties in the movement of an object (earth construction, particular material or field, etc…) to achieve an objective (develop or generalise, integrate mainstream construction, etc…). For the second approach, chosen for the thesis, a bias has been identified in the literature. In particular, there is often a lack of description and conceptualization of the object, the objective, the context and consideration of stakeholder's perspective. This represents a lack of situating from the point of view of situated knowledges theory. From this critique, a new conceptual framework has been proposed. This one will be used for the analysis of the case study whose methodology will be the topic of the next chapter. This new conceptual framework, that recognises contextual situation of studies on barriers and drivers, is a way to move towards situated research.

Finally, this investigation of barriers and drivers to the use of earth in construction helped to identify a lack of situating research in literature. Indeed, some literature use barriers as arguments to justify their research topics. For instance, the low durability of the material is often put forward as a barrier to justify studies on lime or cement adjuvantation. Similarly, the low production rate is often highlighted as a barrier to justify investigating new implementation techniques such as 3D printing. However, these justifications are generally not based on scientific evidence and the validity of the barriers involved are often debatable, according to the context. Therefore, the mobilisation of

supposed *barriers* to the use of earth in construction can be understood as only conveying a bias of a lack of situating (i.e. situated research that ignores itself). This critique will help to establish an autocritique of the introduction of the published article related to the Chapter 1 in the end of the Chapter 6. This corresponds to the aim of the study: situate the knowledge developed in Chapter 1. To achieve this, it is first necessary to analyse the case study, through the lens of the conceptual framework developed in this Chapter. The following Chapter will describe the methodology adopted.

3 Methodology of the case study analysis

Chapter 3 describes the methodology employed for the next chapters of this thesis: a single buildings' case study analysis. The methodology is inspired by science and technology studies to define what is the scope of the study: not only the finished building will be considered but also the design process, involving various stakeholders, the whole being part of a socio-technical system. So, additionally to technical implications, political, economic, organisational and socio-cultural factors will be investigated. The analysis of the building's case study is grounded on document and email analysis combined with an interview campaign with various stakeholders involved in the building's design process. The study is situated in the time between the winning of the competition and the delivery of the building.

1. Introduction

Based on the 'research onion' concept developed by Saunders et al. (2015), this chapter will describe the methodology applied for the analysis of the case study in the thesis. Through this concept, Saunders al. (2015) define different layers to consider while developing a methodology, namely the philosophy, the approach to theory development, the methodological choice, the strategies, the time horizon and the techniques and procedures (Figure 3.50).

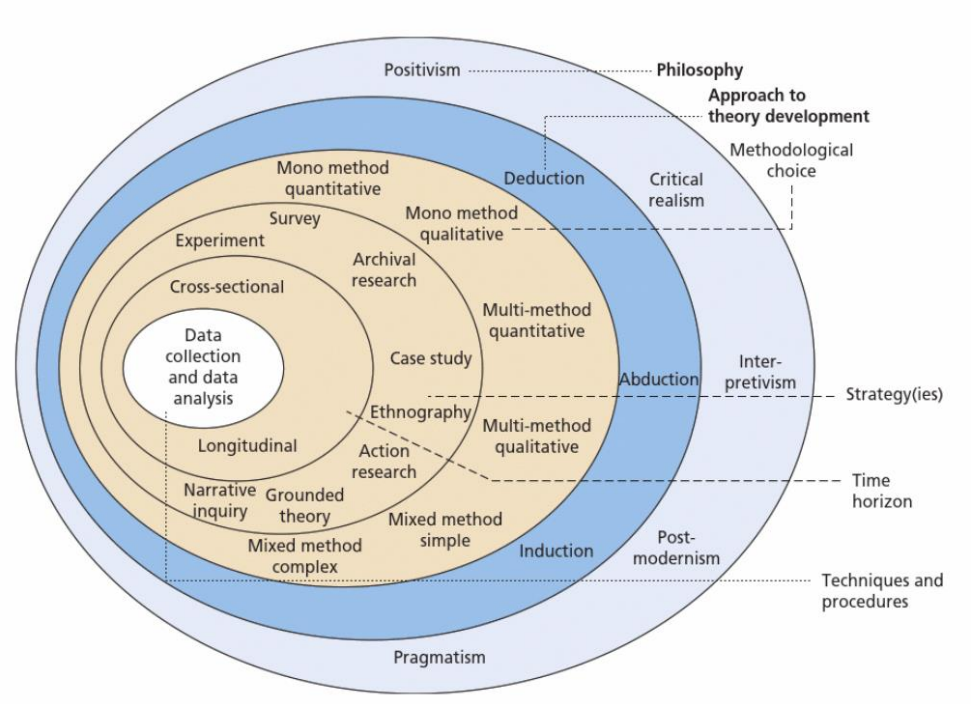


Figure 3.50: The research 'onion' © 2015 Mark Saunders, Philip Lewis and Adrian Thornhill

Although this concept has been developed first in the context of business studies, different authors already adapted it to other fields of research, such as future studies (Melnikovas, 2018), information systems research (Mardiana, 2020) or urban landscape studies (Assadpour et al., 2022), without making major changings of the concept. This concept helped the author to structure and develop the methodology. Therefore, this section will first describe the research paradigm and philosophy adopted, then the methodological choice, strategy and approach (being a single case study qualitative analysis) and finally provides information on the research quality and ethics.

2. Research paradigm and philosophy: toward a socio-technical approach

2.2. Ontology, epistemology, axiology

The research philosophy *refers to a system of beliefs and assumptions about the development of knowledge*" (Saunders et al., 2015, p. 124). It means, that, whether aware or not, during our research we are making assumptions about human knowledge (epistemology), realities (ontology) and the way our own values can influence our research project (axiological assumptions). As these assumptions shape how we understand our research questions, the methods we use and how we interpret our findings (Crotty, 1998), it is important to describe what is the research philosophy we are referring to as a frame to conduct our research.

Ontology "*refers to assumptions about the nature of reality*" (Saunders et al., 2015, p. 127). What is reality? Is there a social reality? Is there a single reality or are there multiple realities? Is reality dependent or independent of the social actors? These are questions that can be asked to address ontology.

Epistemology concerns "*assumptions about knowledge, what constitutes acceptable, valid and legitimate knowledge, and how we can communicate knowledge to others*" (Saunders et al., 2015, p. 127). Questions referring to epistemology could be: How can we know what we know? What is considered acceptable knowledge? What constitutes good quality data? What kinds of contributions to knowledge can be made?

The epistemological choice has already been described in the introduction and is the underlying theme of this thesis. This thesis refers to feminist epistemologies and in particular the theory of situated knowledges proposed by Donna Haraway (Haraway, 1988).

Finally, Axiology refers to "*the role of values and ethics within the research process. This incorporates questions about how we, as researchers, deal with both our own values and those of our research participants*" (Saunders et al., 2015, p. 128). Typical axiological questioning could be: What is the role of values in research? How should we treat our own values when we do research? How should we deal with the values of research participants?

Similarly, to epistemological reflections, the axiological positioning of this thesis has been treated in the introduction, particularly by outlining a "declaration of values".

2.3. Technology dissemination: from a functionalist system view to a socio-technical approach

Through the research and my experience in construction, I have noticed that buildings cannot be seen only as technical objects for which only technical issues arise. Indeed, if we did, it would mean that we would tend to believe in a technological determinism in the adoption or not of earth construction techniques. Technological determinism, which would imply an *"inherent and compelling logic of technical development"* (Rohracher, 2001), has already been underscored as being insufficient to describe technology transfer and the adoption of new techniques or technologies (earth construction techniques in our case) by the science and technology studies (STS) (Akrich et al., 2006, p. 161). Moreover, the study of barriers to the use of earth as a material in construction cannot be considered only a technical problem, as demonstrated in Chapter 2. Authors have shown in the case of "green buildings" that "*the challenge of green buildings is only to a minor extent the search for enhanced technical solutions. What is much more challenging is the social embedding and the socially interactive process of designing, constructing and using buildings*" (Rohracher, 2001). This hypothesis can be extended to the construction of earthen building and it will be verified throughout the thesis. In other words, the choice of a construction material or a construction technique does not only depend on technical choices but is also linked to the social context, the legislation context (regulation for example) or the economic context. To better understand the technology transfer potential of the earth material in everyday construction, all these aspects must therefore be factored in simultaneously. Rohracher (2001) advises considering the technical, organizational, political, and economic factors and the strategies of the stakeholders. In this thesis, the four first categories will be taken and the last one replaced by socio-cultural factors. Indeed, socio-cultural aspects have already been underscored to have a crucial influence on the diffusion of innovation in the building sector (Deshayes, 2012), and in earth construction in particular (Hafez et al., 2023). Besides, these five categories (technical, economic, political, organizational and socio-cultural) have been recommended by authors in earth construction field (Morel et al., 2021b). Conclusively, choosing these categories to analyse the case study means adopting a socio-technical approach, inspired by STS, for this thesis. In particular, as recommended by Rohracher:

> *"one approach to better understand and subsequently overcome barriers to sustainable buildings is to analyze buildings and the actors involved as* ***socio-technical systems"*** *(Rohracher, 2001).*

2.4. Buildings as socio-technical systems: the research philosophy of the thesis

For the study, how designers addressed the barriers to using earth construction to build a modern earth building with load-bearing rammed earth façades will be examined. To do so, as described above, the socio-technical approach recommends to consider buildings as socio-technical systems. A socio-technical system is a concept provided by STS as a system composed of the technical object (here the building) and all the relationships between all the stakeholders (architects, engineers, … but also with the building itself) (Akrich et al., 2006). To illustrate the relationship between the building (virtual during the design) and other stakeholders, it will be seen throughout this thesis that the choice of earth material has implied different relations between the stakeholders. As an example, the introduction of academics and the mason early in the design which has changed relationships between the other stakeholders.

Inspired by the STS and a socio-technical approach, defining the research philosophy (Ontology and epistemology) adopted in the thesis, a building can be defined as:

The result of a process, involving designers, who make assumptions about the building's place in the social environment (including the needs of the end-users), and involving different stakeholders (structural engineer, control officer, contractors, project owner, other engineers, …), at different times, between which different types of interactions occur. Considering decisions to overcome barriers and problems arising during the design phase involves accounting for technical, economic, political, organizational, and socio-cultural factors and to some extent the strategies of the stakeholders. All these interactions, factors, and the result itself (the building) correspond to the socio-technical system under study. Figure 3.51 summarizes the approach. It should be noted that this figure is only conceptual and is therefore debatable and non-exhaustive. For instance, the scale of the project might influence the involvement of the stakeholders where for example for small houses, architects (at least in France) are not required and contractors can play this role. Additionally, end-users have not been represented as there were not integrated into the scope of the thesis for the case study analysis. Then, while no distinction has been made in the interactions in the figure, it should be noted that the nature of the interactions between stakeholders can be very different. For instance, the control officers will control the work of the designers and contractors, while they will provide an opinion to the project owner (see Chapter 4 for more details on the role of the control officers). Finally, the circle representing what is described as designers can vary according to the project when different stakeholders can actively participate in the design of the building. Chapters 4, 5, and 6 will emphasize on the role of the different stakeholders in the case study.

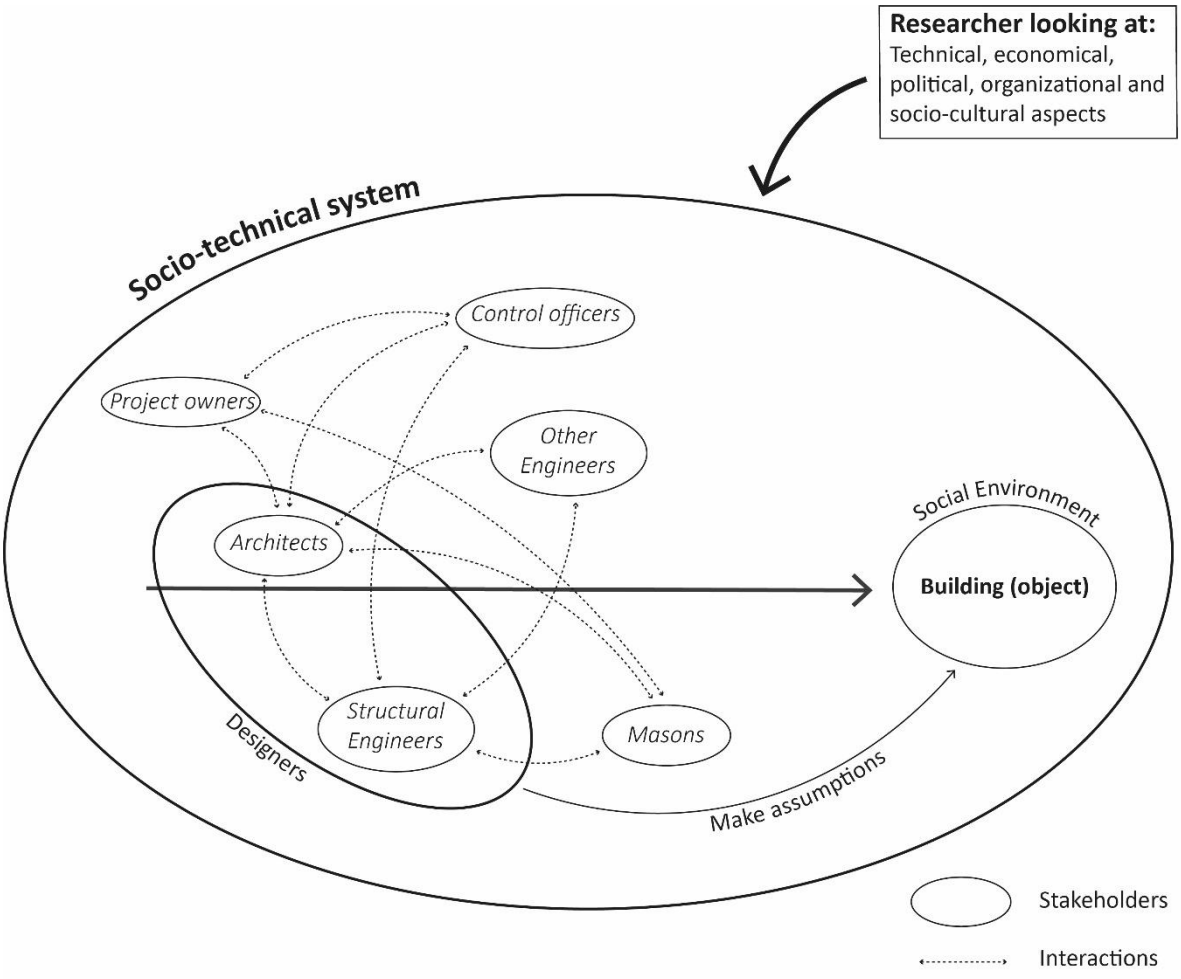


Figure 3.51: Scheme of the research philosophy approach. The scheme is not exhaustive and is just a conceptual representation of the definition chosen for building design

Now that the socio-technical approach used in this thesis is defined as a research philosophy it is major to highlight the limitation of the approach. Indeed, although concepts of sociology of sciences and techniques have been used, I am not advocating for a PhD in this discipline. The PhD thesis does not aim to question the concepts involved, but only to use and apply them to provide a framework (basically, what I look for) for analysis.

3. Methodological choice, strategy and approach

This section aims to describe the methodological choice (qualitative, quantitative or mixed) and the methodological strategy (single case study) employed for this thesis and in particular for Chapters 4, 5 and 6. Indeed, this does not include the Chapter 1 and 2 which were treated with a separate methodology.

3.2. Method choice: qualitative, quantitative or mixed?

3.2.1. Definitions, advantages and disadvantages

Research methods include quantitative, qualitative or mixed methods. Creswell (2013) defines the quantitative method as:

> *"an approach to testing objective theories by examining the relationship between variables. These variables, in turn, can be measured, usually by instruments, so that numerical data can be analysed using statistical procedures" (Creswell, 2013, p. 32)*

The advantages of quantitative methods include the high level of generalizability and the possibility of studying a "*large number of cases for certain aspects in a relatively short time frame*" (Flick, 2015), however, they may lack relevance on studied aspects and the meanings of these could be insufficiently taken into account.

On the other hand, qualitative research is "*an approach for exploring and understanding the meaning individuals or groups ascribe to a social or human problem*" (Creswell, 2013, p. 32). Qualitative methods focus on the search for meaning and "the importance of rendering the complexity of a situation" (Creswell, 2013, p. 32). Providing "*detailed and exact analyses of a few cases […], in which participants have much more freedom to determine what is relevant for them and to present it in its contexts*" are advantages of the qualitative method (Flick, 2015). Meanwhile, these studies are usually time-consuming and generalizability is limited. However qualitative researches do not seek a generalization similar to quantitative researches.

The distinction between qualitative and quantitative research is usually made "in terms of using words (qualitative) rather than numbers (quantitative)" (Creswell, 2013, p. 32). In some cases, to combine the strength of these research methods and when it is relevant to the research question, researchers use mixed methods. The latter involves collecting both quantitative and qualitative data and using "*distinct designs that may involve philosophical assumptions and theoretical frameworks*." (Creswell, 2013, p. 32). It is argued that the advantages of the mixed method lie in overcoming the biases and weaknesses of quantitative and qualitative methods by combining the collection of each form of data (Creswell, 2013, p. 43).

Whether one chooses quantitative, qualitative or mixed method, it is essential to look at what type of answers bring the choice of method to the research question. A careful look at the literature will help to categorize the types of answers to position the research carried out for the thesis.

3.2.2. What type of conclusions brought the method choice in the literature on the research question?

3.2.2.1. Quantitative

Quantitative research related to the research topic (RQ2.2[83]) was usually based on a questionnaire survey. This type of research offers conclusions mainly on the ranking factors (See for example (El-Sawalhi and Ajwa, 2013; Owino et al., 2014b; Spišáková and Mačková, 2015b) with more or less specifications in the ranking. For example, Lakys et al. (2022) categorized drivers according to stakeholder perspectives (Lakys et al., 2022), while most studies have not reached this distinction.

These methods, aiming at generalization of the results (see previous section) can however lead to questionable recommendations if they lack of contextualization:

> *« **Since the highest ranked problem of houses built with locally available materials was the low strength of the houses** and the last ranked major problem was easy erosion of the local materials**, future researchers should consider researching into how to reinforce the mechanical and durability properties of the local materials** with industrial and agricultural wastes or other conventional materials to ensure long-lasting of the houses built with local materials. » (Danso, 2013, p. 6)*

Indeed, the questionnaires in this study were addressed to earthen households in a specific context (Dorongo community in Ghana). Therefore, generalizing the low strength, although the highest ranked problem in this study, to meet the recommendation to perform further research on the reinforcement of the mechanical properties of earth material seems debatable. For instance, a recent study has highlighted that social barriers are the priority to address, in the context of CEB in Egypt (Hafez et al., 2023). Of course, the recommendation of Danso (2013) could still be relevant in the particular context of the study.

3.2.2.2. Qualitative

Compared to the quantitative approach, qualitative research generally allows for a deeper understanding of potential factors affecting the use of earth in construction, using interviews or case study analysis. This is achieved mainly by thematic classification of factors in different categories: for example technical, economic, organizational, socio-cultural, political and environmental (Morel et al., 2021b); "*technical (based on facts related to earthen construction), socio-economical (based on emotions that relates to economic status) and, political and educational (based on non-household*

[83] What are the barriers and drivers to the use of earth in construction and how to study it?

policies and initiatives" (Kulshreshtha et al., 2020, p. 4). The interconnection of the different factors is also studied by the qualitative method (see for instance (Sameh, 2014; M. S. Zami, 2021a)).

It should be noted that only a few studies, including two research papers (Morel et al., 2021b; Zawistowski et al., 2020), three master's thesis (Hassani, 2018; Leylavergne, 2012; Villar, 2020) and two reports (AsTerre, 2013; GT biosourcés action 18c, 2012), investigated the research question in the French context using qualitative methods.

3.2.2.3. mixed-method

Finally, various mixed methods could be found in the literature, addressing the research question and bringing different types of conclusions: some authors classified factors by the quantitative method, then deepen the understanding using the qualitative method (Aghimien et al., 2016b; Ben-Alon et al., 2020a). Others established themes through a qualitative method and then ranked them through a quantitative method (Samarasinghe and Falk, 2022); Finally, some authors used the Delphi method[84] to rank factors thematized previously through literature reviewing (Zami and Lee, 2011b).

3.2.3. Method choice for the thesis: qualitative

Only a few studies have investigated the research question in France through qualitative data. Moreover, as the objective of this thesis is to at deepen the understanding of barriers and how to overcome them, in particular to situate the knowledge of Chapter 1, therefore a qualitative approach has been chosen for data collection.

3.3. Methodological strategy: a single case study

In this section the choice of a single case study as a methodological strategy will be depicted. First by providing a rationale for this choice and then data gathering will be outlined. The method employed for the single case study analysis, based on both documents and interviews analysis is represented in Figure 3.52.

[84] Delphi method was initially defined as a way of obtaining consensus of opinion of a group of experts by using series of questionnaires with controlled opinion feedbacks (N. Dalkey, 1963). Nowadays, different types of method exist with no requirement for reaching consensus (Landeta, 2006). The aim of the method is to structure a group communication process to determine, predict and explore a group of expert's attitudes, needs and priorities regarding a complex issue (Hasson and Keeney, 2011; Okoli and Pawlowski, 2004), by using both qualitative and quantitative analysis (Belton et al., 2019).

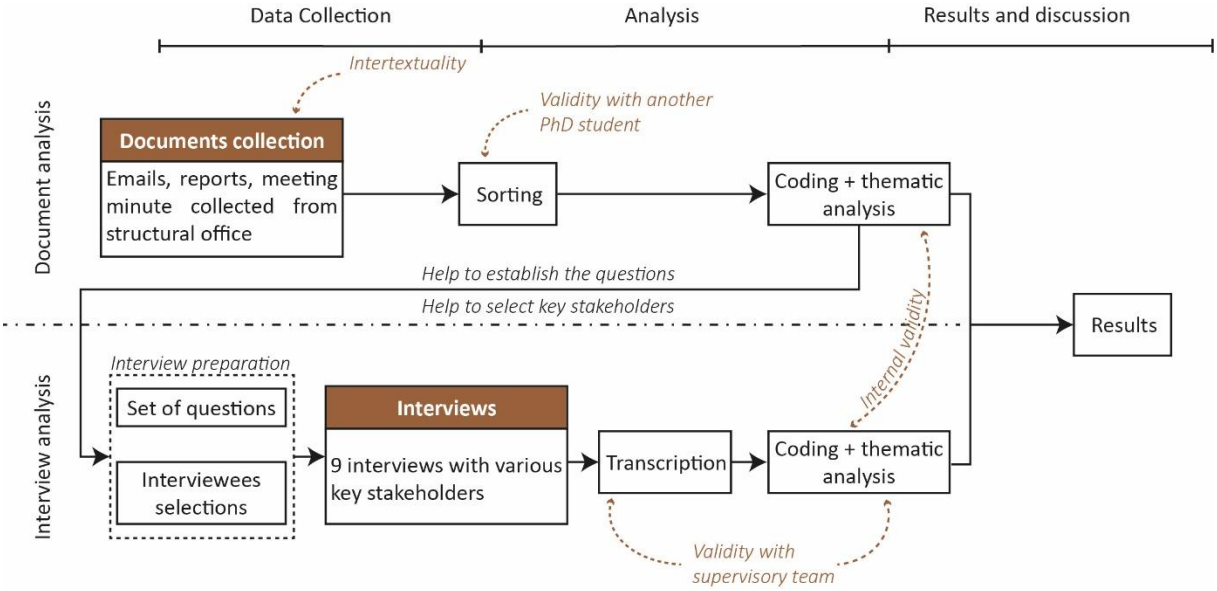


Figure 3.52: Schematic representation of the different step of the methodology employed highlighting the different sources of data (documents and interviews).

3.3.1. The rationale for choosing a single case study

As defined by Bryman, "*the term 'case' associates the case study with a location, such as a community or organization. The emphasis tends to be upon an intensive examination of settings*" (Bryman, 2016a, p. 67). Exploring in depth a case means looking at "*the complexity and particular nature of the case in question*" (Bryman, 2016a, p. 66). For single case study research design, it can refer to "*a single community*", "*a single school*", "*a single family*", "*a single organization*", "*a person*" or "*a single event*" (Bryman, 2016a, pp. 66–67). While Creswell (2013) considers a case study as a qualitative research design (Creswell, 2013, p. 290), Bryman (2016) agrees that there is a tendency of using qualitative strategies associated with a case study design. However, "*case studies are frequently sites for the employment of both quantitative and qualitative research*" (Bryman, 2016a, p. 68).

In the earth construction literature, case study analysis could focus on specific buildings - either multiple case studies (Gasnier, 2019; Sameh, 2014) or a single case study (Zawistowski et al., 2020) - but also specific construction processes or techniques (See for example (Lakys et al., 2022), for a case study analysis of CEB acceptance in Kuwait or (Hafez et al., 2023) for CEB in Egypt).

Given the issue of defining barriers, and particularly the need for contextualisation (see Chapter 2 section 5), the analysis of case studies has the advantage of being "*bounded by time and activity*" (Creswell, 2013, p. 290). Indeed, it is possible to define a beginning and an end in the design process of a building. In our case, the beginning is the success of the competition and the end is the handover of the building. It is assumed for this thesis that focusing on a single case study allows to provide a proper definition of "*barriers*" and "*drivers*" using the conceptual framework proposed in Chapter 2.

Indeed, Chapter 4 will provide such definitions including an explanation of what means “objective” and “object” (see the conceptual framework of Chapter 2) in the case study analysis. Defining the building with the boundaries of the analysis thus helps to be clear on the “*unit of analysis*” (Bryman, 2016a, p. 68), and not fall into the bias of lack of contextualisation highlighted in Chapter 2, section 5. In other words, this could represent a lead to conduct situated research.

As described by Yin (2009), different types of case studies exist, including “*the critical case*”, “*the extreme or unique case*”, “*the representative or typical case*”, “*the revelatory case*” or “*the longitudinal case*” (Yin, 2009), from which the case study can be a combination of (Bryman, 2016a, p. 71). In the thesis, as the chosen case is unique and an intensive literature review was carried out to build theories on the barriers to the use of earth before analyzing this case, we could consider the type of case as a combination of, respectively, an “*extreme or unique case*” and a “*critical case*”.

Three reasons can explain the choice of single case study analysis for the thesis: (1) no literature in the field of earth construction has explored the research question through an in-deep investigation of a single case study, (2) it is believed by the author (and will be demonstrated in Chapter 4) that using a single case study allows to situate the research by using the conceptual framework developed in Chapter 2, and (3) describing a single case study will allow highlighting the obstacles actually met by the stakeholders in a specific context.

Finally, the choice of the specific building as a case study rely on two main reasons: (1) the opportunity for data collection by the author of the study; (2) and the particularities of the building being a showcase (at least in the French earth construction context as it will be demonstrated in Chapter 5).

3.3.2. Data gathering and analysis: various sources

3.3.2.1. Document analysis

In this section, we will detail the protocol applied to analyse the documents (emails, reports, meeting minutes) of the case study (Data collection, sorting and analysis). The bullet point protocol used for the analysis is available in Appendix C1.

Data collection

As Bryman reminds us, various documents can be analyzed for a case study, such as online discussion groups, blogs, email, social networking sites, etc (Bryman, 2016a, p. 556), and it is generally advised to combine these documents to improve trustworthiness. To assess the quality of the documents collected, Scott’s four criteria (Bryman, 2016b, p. 546) were followed:

- Authenticity: Is the evidence genuine and of unquestionable origin?

- Credibility: Is the evidence free from errors and distortions?
- Representativeness: Is the evidence typical of its kind, and, if not, is the extent of its atypically known?
- Meaning: Is the evidence clear and understandable?

It is important to recognize documents for what they are, i.e. "*texts written with distinctive purposes in mind, and not as simply reflecting reality*" (Bryman, 2016a, p. 561). For instance, meeting minutes tend to make potential conflict or tension in the meeting between stakeholders invisible, as they are meant to be read by those stakeholders (Bryman, 2016a, p. 555). That's why interviews are necessary to buttress the interpretation of the data. In this study, the data collected from the project were: emails, meeting minutes, technical documents, and interviews. These will be described in the next section, while other documents come from archives provided by some stakeholders involved in the project. These data cover the case study from January 2016 to January 2021. Once collected, the data was sorted to select those that were relevant to the research question.

Data sorting

The archives collected were all documents relating to the five buildings in possession of the structural engineer's office. This might introduce a bias by making invisible some documents that were not in possession of the structural engineer's office. However, these hidden documents might be marginal as structural engineers were involved in most of the exchanges during the project. Besides, the interviews allowed us to complete the data and reduce this bias. A first sorting was necessary to collect only the documents related to the case study. A second sorting was then applied to select all emails, plans, or reports, concerning the façades of the building, in particular information on the use of rammed earth. This sorting step was conducted with another PhD student. This improved the validity of the procedure by peer debriefing (see section 4.1).

For more visibility on the project, it was decided to sort all the documents chronologically into an Excel spreadsheet, distributed according to the different phases of the project (See Chapter 4 for a description of these phases). For each document, the source, to be able to come back to it, the date, the type of document (including email, report, and meeting minutes), the author of the document and recipients, if relevant, have been notified.

Sorting was also useful to understand the "*inter-textuality*" defined as the "*interconnectivity of documents*". Indeed, "*any documents must be viewed as linked to other documents because it invariably refers to and/or is a response to other documents. Other documents are part of the context*

or background to the writing of a document." (Bryman, 2016a, p. 255). After sorting, 839 emails, 11 meeting minutes, plans and couple of technical reports were selected.

Data analysis

For the analysis, the first step was to implement the sorted data into Nvivo (qualitative research analysis software). Then, a first screening of the data was required to get used to it, initiating the analysis by identifying key moments or procedures in the design process. Ones the author was accustomed to the data, the coding process could begin, by highlighting various problems faced by the design team during the design process. Coding can be defined as "*attaching one or more keywords to a text segment to permit later identification of a statement*" (Kvale, 2007, p. 105). Finally, these codes were assembled under themes and sub-themes, following the principles of thematic analysis, looking for information on the following set of questions:

- Is it a technical, organizational, political, economic, or socio-cultural problem?

- Which actors highlighted the problem?

- At what time during the project?

- What are the different causes and sub-causes of the problem?

- What solutions are considered? What solutions have been adopted?

- Which actors proposed the solutions?

- At what time?

- Is it a technical, organizational, political, socio-cultural or economic solution?

As explained by Bryman (2016), thematic analysis (i.e. establishing themes and sub-themes) is "*the product of a thorough reading and rereading of the transcripts or field notes that make up the data*" (Bryman, 2016a, p. 579). Different characteristics can define what a theme is. It is considered as a "*category identified by the analyst through the data*" that pertains to the research question. This category is developed by a coding process and serves as the foundation for the researcher's theoretical comprehension of the data (Bryman, 2016a, p. 580). For the identification of themes, a repetition criterion was followed, said to be the most common, completed by relevance to the research question and concordance with the analysis of the literature.

3.3.2.2. Interviews analysis

To establish the interview survey, the author followed the seven steps proposed by Kvale (2007), including thematizing ("*formulation of hypotheses*"), designing ("*planning the interviews*"), interview, transcription, analysis, verification (checking "*reliability and validity*") and reporting (Kvale, 2007, pp. 36–37). Details are provided in the following sections. The preparation of semi-structured interviews is first explicated. Then the sampling and interview process are detailed and finally, the method used for interview analysis is underscored.

Preparation of semi-structured interviews

From the document's analysis, described above, the set of questions has been established. Indeed, parallel to the reading and analysis of the data, when questions occur from it, there were written in a separate document with a link to the reference in the data, the stakeholders involved or to whom to ask this question and the theme, sub-theme, and sub-sub-theme, to which the question was related. Besides, questions for clarification (for instance on the order of the events during the design process) were also collected.

From this first series of questions, a general interview grid was established with different themes to be addressed during the interviews and specific questions related to these themes. Then, this grid was adapted according to the type of stakeholders to emphasize certain themes more related to these stakeholders. An example of this grid is provided in appendix C2.

This process of setting up interviews can refer to a semi-structured interview. Indeed, it includes "*a sequence of themes to be covered, as well as some prepared questions*" (Kvale, 2007, p. 65). However, semi-structured interviews, as is our case, offer "*openness to changes of sequence and question forms to follow up the answers given and the stories told by the interviewees*" (Kvale, 2007, p. 65). As Rowley (2012) pointed out, semi-structured interviews can take different forms "*with varying numbers of questions, and varying degrees of adaptation of questions and question order to accommodate the interviewee*" (Rowley, 2012). In our case, the number of questions was more or less consistent, but the interviewer adapted the order and certain specific themes according to the profile of the people interviewed making sure to address all the themes during the interview.

Once the interview questions and method have been established, and validated by the supervisory team. Pilot studies were carried out to improve the grid and the interviewer's skills. During the pilot studies, the interviewer noticed some biased questions which were modified accordingly. Six pilot interviews were carried out with two architects, two control officers, one earth expert and one public project owner, that had no link with the case study. These pilot studies also helped to address the bias related to the involvement of the author in the project, particularly with the structural engineer.

However, these interviews were not added to the analysis as the interviewees were not involved in the project.

Interviewees sampling

Given the emphasis on the design process and the choice of a single case study method, the sampling was necessarily purposively stakeholders of the building project. The aim was to obtain various opinions about the design process and the problem encountered, as is commonly sought in purposive sampling during an interview survey (Bryman, 2016a, p. 418). Therefore, interviews with various professionals involved in the project were carried out, including: one control officer (employee in the control office involved in the project); a third-party controller (being also a control officer but from a different company than the first, involved during a short period on the project); one professional from a standardization organism (involved during a short period on the project); one of the architects; one person from the project owners office; one engineer from the structural design office and one from the thermal engineering office; one mason from the contractors' company that built the rammed earth façades; and finally one academic involved in the project, for a total of 9 interviewees (all interviewees approached accepted the interview). The sampling was selected based on the occurrence of the different stakeholders from the email analysis and focused on key stakeholders. Then, the question "What were the key stakeholders of the project" was asked to all the interviewees to verify that no key stakeholders were missed in the sampling. Table 3.14 gathers information on the profile of the interviewees and interviews. The selected interviewees were involved at different times and periods in the project, as shown in Figure 3.53. Although the figure represents the involvement in a period in the project, it should be noted that the degree of involvement is not represented because it is difficult to assess.

Table 3.14: Table gathering information about interviewees and interviews

Code	Visio / face to face	Interview duration	Profession	Year of experience in the construction sector	Year of experience in earth construction	Number of projects followed
R01	Face to face	1h15	Academic	N/A	11	2
R02	Face to face	58min	Controller	-	-	-
R03	Face to face	41min	Project owner	30	5	1
R04	Visio	54min	Control officer	-	-	-
R05	Visio	1h15	Standard organisation employee	20	7	15

R06	Face to face	49min	Thermal engineer	15	6	4
R07	Face to face	50min	Architect	-	-	-
R08	Face to face	2h	Structural engineer	11	7	4
R09	Face to face	45min	Mason	45	42	40

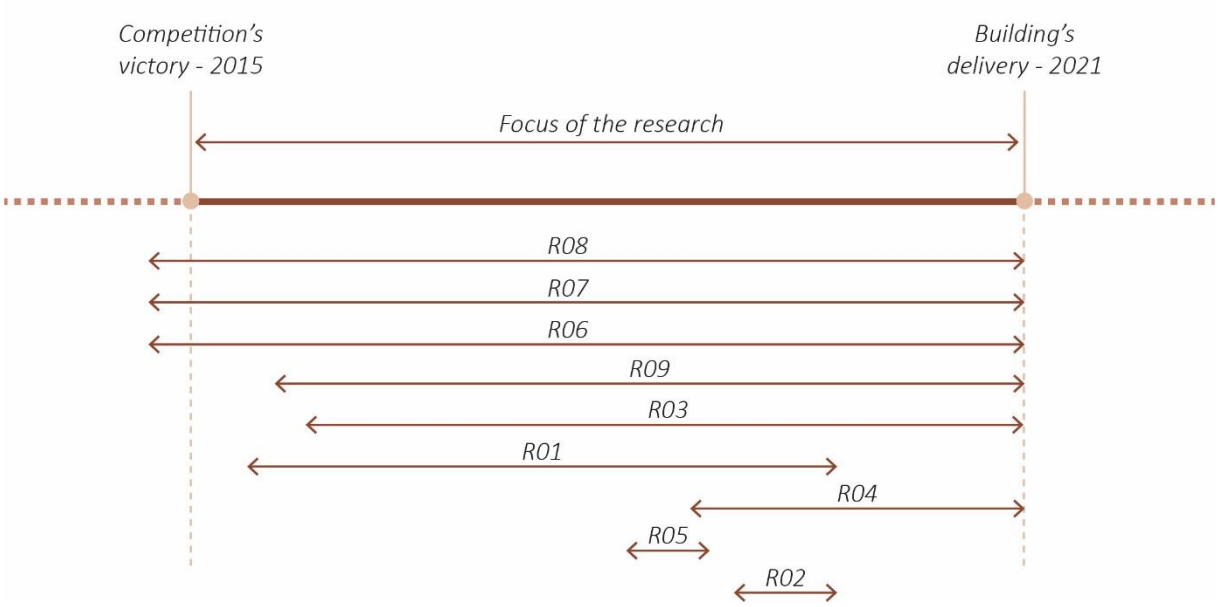


Figure 3.53: Timeline involvement of interviewees in the case study

The number of interviews may differ from study to study and is a balance between not being too small to reach "*data saturation, theoretical saturation, or informational redundancy*" and not so large "*that it is difficult to undertake a deep, case-oriented analysis*" (Bryman, 2016a, p. 425). Thanks to the combination of interview and document analysis, data saturation[85] was reached in this study. Finally, the number of interviewees is also a common number of interviews conducted (Kvale, 2007, p. 44), where Kvale states that "*amount of interviews tend to be around 15±10*".

[85] The data saturation corresponds to the point when while carrying new data, following the same method, no new information is discovered.

Interview process

Concerning the process carried out for the interview, different times can be distinguished, in particular the introduction, the core and the end of the interview.

in the introduction, for each interviewee, as recommended by (Burke and Miller, 2001), the following information was provided: introduce myself (PhD student, the year of study); the body where the PhD is undertaken; the general topic of the study; the confidentiality of interviewee responses; the use that will be made of the information and an estimate of the duration of the interview. Consent where then asked to the interviewees to pursue the interviews.

During the interview, questions were asked to the interviewees according to the established grid as described in the previous section. As Kvale (2007) highlighted, "*The quality of an interview relies not only on the questions asked; the way the interviewer reacts after an answer may be just as important, such as by allowing a pause for the interviewee to continue an answer, by probing for more information and by attempting to verify the answers given*" (Kvale, 2007, p. 65). Therefore, the researcher adapted the questions to encourage the interviewees to go further in their initial answers. In addition, the researcher adapted the order of questions to stick to the answers of the interviewees, taking care to touch on all the themes. However, each interview was structured following the main three themes: asking "In your opinion, what were the main problems encountered during the project? What solutions were found? What were the conditions for the project's success?"; asking complementary questions based on document analysis to obtain details on the previous questions; and finally asking "What were the key stakeholders of the project?" which helped to validate the sampling and avoid missing any key stakeholders for the interviews.

The duration initially planned was between 45min to 1h. However, the researcher was keen to receive any additional information from the interviewees related to the research question. In particular, one interview lasted longer than the others because the interviewee was particularly talkative. The duration of the interviews is presented in Table 3.14.

Final closed questions (relating to experience in construction and earth construction more specifically, number of projects followed, membership of an earth association and trainer in earth construction) were asked at the end of the interview, as recommended by (Burke and Miller, 2001). Asking these questions at the end avoids asking "*participants to guess your hypothesis, or to think about how the answers to such questions 'are supposed to' affect their responses*" (Burke and Miller, 2001).

The interviews were carried out either by Visio conference (mainly due to the geographical distance between the researcher and the interviewees) or face-to-face. Most of the interviews were tape-

recorded except for the mason. The latter did not accept to be quoted in the thesis, which explains why no quotation of the mason can be found throughout the manuscript.

Interview analysis

In qualitative research, it is difficult to define exactly when the analysis began in. In particular, in the interview procedure, the researcher usually produces analytical insights: during the interview, by adapting questions and by actively listening to the interviewees or between interviews by adapting the set of questions. Nevertheless, this part will describe the analysis process once the interview campaign was over.

As a first step, a transcription of the interviews was necessary. As recommended by Schmalz et al, transcriptions were made by the author of the thesis (Schmalz et al., 2021). As the interviews were conducted in French, the transcriptions were also made in French. Different types of transcription exist and the choice must be adapted according to the method of analysis chosen by the researcher. In our case a "*clean read or smooth verbatim transcript*" (Mayring, 2014, p. 45) was chosen, meaning that the transcriptions were made "*word for word, but all utterances like uhms or ahs, decorating words like, right, you know, yeah were left out. A coherent text, simple to understand but representing the original wording and grammatical structure is produced. The shortened articulations and dialects are translated into standard language (c'mon = come on).*" (Mayring, 2014, p. 45). Indeed, this transcription protocol had the advantage of a good balance between ease of reading for more advanced thematic analysis and limited loss of information. Moreover, the different utterances, useful, for instance, for the analysis of psychoanalytical text, were not analyzed in this study.

Once all the interviews have been transcribed, the thematic analysis can begin. The researcher opted for an incremental process. First, three interview transcripts were fully read and coded using Nvivo software. Then a first thematization was carried out in search of repetition, referring both to "*recurrence within a data source (for example, an interview transcript or document) or, as it is most often the case, between data sources (for example, a corpus of interview transcripts or documents)*" (Bryman, 2016a, p. 580). Finally, the other transcriptions were read and coded following and completing, if necessary, the first thematization. Particular attention was taken when establishing the themes to stick to the research questions, as recommended by Bryman (2016). In addition, consistency with the thematization carried out for the document analysis described above was sought.

As a matter of internal validity (for the quality of the research which will be described in detail in the next section), the coding process as well as the thematization for the analysis of the interview were rechecked by the supervisory team. Finally, the quotation useful for the thesis were first selected in French, then translated by the author and the translation was rechecked by the supervisory team to

verify the meaning consistency. It has been decided to not let appear the original versions of the quotations, as it was considered risky for the anonymity of the interviewees. Indeed, as the project is well-known, the anonymity of interviewees is limited and it was preferable not to have a direct quotation that could be prejudicial for the interviewees.

4. Research quality

Assessing the quality of research strongly depends on the research method used, whether quantitative, qualitative or mixed. Different terms are commonly used, such as validity, reliability or transferability. In this part, these terms will be defined and discussed according to the study carried out for this thesis, namely a qualitative study of a single case study, involving interviews and the analysis of documents.

4.2. Validity

In ordinary language, validity can refer to "*the truth, the correctness and the strength of a statement*" (Kvale, 2007, p. 122). On the other hand, to argue for valid scientific knowledge produced by qualitative research, a broader definition of validity can be used: "*Validity pertains to the degree that a method investigates what is intended to investigate*" (Kvale, 2007, p. 122). The validity of argument in qualitative research will therefore rely mainly on the correct definition of the research question (See Introduction of the thesis), the analytical framework (section 3 of this chapter), and a detailed and well-founded description of the data analysis. Qualitative validity is, therefore, a question of the accuracy of the findings, for which different strategies can be employed, described by Creswell (2013), such as triangulation; use of member verification; use of a rich and thick description; clarifying bias; spending extended time in the field; peer debriefing. Table 3.15 describes the actions adopted taken to improve the validity of the results according to these different strategies.

Table 3.15:Table referencing the different validity procedures proposed by Creswell (2013) and actions taken by the researcher in accordance

Validity procedures (from (Creswell, 2013))	**Actions taken by the researcher**
Triangulation "*If themes are established based on converging several sources of data or perspectives from participants, then this process can be claimed as adding to the validity of the study*"	Different sources have been used to establish the themes: - The document analysis is based on emails, reports, meeting minutes - The interviews carried out with various stakeholders

	Cross-checking these various sources of information improved the validity of the study. In particular, as the interviews were carried out two years after the end of the project, the interviewees sometimes did not remember all information, but the use of email helped to replace the accuracy of the information provided during the interviews in the timeline of the project.
Using member checking "*taking the final report or specific descriptions or themes back to participants*" to assess the accuracy	Transcripts were sent to interviewees for validation and additional feedback. Due to a lack of time for the study, the themes and analysis were not validated by the interviewees but by the supervisory team only.
Using a rich and thick description "*When qualitative researchers provide detailed descriptions of the setting, for example, or offer many perspectives about a theme, the results become more realistic and richer*"	A rich and thick description of the project is provided in Chapters 4, 5 and 6.
Clarifying the bias "*Good qualitative research contains comments by the researchers about how their interpretation of the findings is shaped by their background, such as their gender, culture, history, and socioeconomic origin*"	For this study, although aware of his gender, culture, history, and socioeconomic background, the researcher felt that the biases from these sources were difficult to assess. Moreover, as this study is not a sociological report, these biases may not be relevant or at least negligible. However, other sources of bias may come from the researcher. Indeed, the researcher worked with various stakeholders of the case study, in particular, he carried out an internship within the structural design office involved in the case study. To avoid any bias related to this

	background, the researcher adopted different strategies: - Significant waiting period (1 year) between the end of the internship and the start of the analysis of the documents. - Pilot studies with earth construction stakeholders different from thestructural engineers to address the potential bias of having been involved in the structural design office of the project. - Finalisation of the interview campaign with the structural designer of the case study. This allowed me not to be influenced by the answers of the structural engineer for the other interviews. Those strategies have made it possible to move away from the "company philosophy" of the structural design office.
Spending prolonged time in the field "*In this way, the researcher develops an in-depth understanding of the phenomenon under study and can convey detail about the site and the people that lends credibility to the narrative account*."	A significant amount of time was spent by the researcher in the field: The researcher works for a year on the case, through two successive internships (this involved potential bias discussed above); the data analysis started in April 2022 and ended in April 2023 with constant back and forth to the data until the writing of the thesis. This helped to gain objectivity.
Peer debriefing "*This process involves locating a person (a peer debriefer) who reviews and asks questions about*	Different peer debriefing processes have been put in place to improve the validity of the study: - Publications in peer-reviewed journals

the qualitative study so that the account will resonate with people other than the researcher."

- Discussion with the supervisory team at each stage of the analysis (Discussing the research questions, the objectives, the choice of the case, the methodology, the sorting and analysis of documents, the choice of interviewees, the set of questions, and the thematic analysis, … etc).
- Discussion with another doctoral researcher working on a similar subject, with a background in the sociology of science and techniques.

4.3. Reliability

Reliability refers to the consistency of the researcher's approach and analysis across different researchers or projects (Creswell, 2013, p. 251) or periods (Kvale, 2007, p. 122). Different strategies were used to increase the level of reliability of the project.

Concerning the analysis of the document, the sorting was carried out with another PhD researcher, to cross-check its consistency. As suggested by Creswell (2013), the coding was constantly compared with the data, including memos and the description to avoid that there was no "*drift in the definition of codes, shift in the meaning of the codes during the process of coding*" (Creswell, 2013, p. 251).

Regarding the method used for the interviews, reliability problems appear in different phases. In particular, consistency issues during the transcription phase can arise as different transcribers could lead to different transcription. The transcription method has been described in detail above (section 3.2.2.2). For the analysis, the coding process was cross-checked with the supervisory team to verify the reliability of the coding as well as thematization. Similarly, for the document analysis, the coding of the interviews was systematically reported to the data sources.

4.4. Transferability

Finally, transferability refers to the level of generalization of the results allowed by the chosen research method. This question is important because one criticism of the case study is "*that findings deriving from it cannot be generalized*" (Bryman, 2016a, p. 71). To avoid misunderstandings, it should be noted that the researcher does not seek to generalize the results when investigating a single case study.

Indeed, "*case study researchers do not delude themselves that it is possible to identify typical cases that can be used to represent a certain class of objects*" (Bryman, 2016a, p. 70). Therefore, this study does not aim to describe a typical earth construction process that can be transferable to any case in any socio-economic situation. On the contrary, particular attention will be paid to situating the case in its context (see Chapter 4). It is indeed argued that the study of barriers and drivers is context-dependent, as explained in Chapter 2.

The aim of this study is therefore to describe in depth the research question in a very specific case to go further in the description of the barriers and drivers and does not seek to generalize the results to other cases. However, the description of a particular case can be a basis either for future research or for professionals wishing to build with earth. Besides, the method proposed in this Chapter is transferable. Moreover, this method will be depicted in Chapter 4 as being able of addressing the research question about barriers and drivers without falling into the bias of lack of situating as described in Chapter 2. Therefore, this method could help further research on this topic.

5. Research ethics

The researcher has followed the deontology principles described in the French charter[86], adapted from the equivalent European charter of deontology of research. Ethics in research arise from the research in practice, but the environment upheaval makes it necessary to adopt ethic principles toward the environment (as already introduced in the introduction of this thesis).

5.2. Ethics in practice

For qualitative research, Bryman (2016) describes four main topics where ethical issues can arise: (1) harm to participants, (2) lack of informed consent, (3) invasion of privacy and (4) deception. The harm caused to participants refers to any harm (physical, stress, loss of self-esteem, …) the research and/or researcher could cause to participants. "*Advocating care over maintaining the confidentiality of records*" is a means of addressing the issue of harm to participants in qualitative research (Bryman, 2016a, p. 135). A certain level of anonymity and confidentiality must therefore be achieved. In our case, the anonymity of the respondents was respected between respondents during the interviews and also in the PhD report. Quotes from interviews have been carefully selected to avoid identification of participants and the original version in French has not been introduced in the thesis to avoid any recognition. However, as the project is described (Chapter 4) in the thesis for research purposes, the bodies involved in the project have been cited, with their agreement. Therefore, quotations have also been carefully selected taking into consideration the potential consequences for these bodies, to avoid

[86] https://comite-ethique.cnrs.fr/charte/

any harm. Finally, as "*it is very difficult, though by no means impossible, to present field notes and interview transcripts in a way that will prevent people and places from being identified*" (Bryman, 2016a, p. 136), it has been decided to not integrate transcripts in the appendix of the thesis report.

Lack of informed consent should be avoided for ethical purposes. As defined by Bryman (2016), "*the principle means that prospective research participants should be given as much information as might be needed to make an informed decision about whether or not they wish to participate in a study*" (Bryman, 2016a, p. 138). At the start of each interview, all information was provided to the interviews, including information on the research subjects, the purpose of the investigation, and the possible risks and benefits from participation (although those are quite limited and mainly withdrawn by anonymity) (Kvale, 2007, p. 27). Then, once transcribed, the interview transcript was sent to the interviewees for validation. Simultaneously, a reminder of the purpose of the study, the potential use of the data and anonymity was provided to the interviewees. An opportunity was given to them to opt out of the study or to highlight a portion of the transcripts that they did not want to use for research.

Another ethical concern described by Bryman (2016) is the invasion of privacy. Respondent privacy is closely linked to informed consent. Indeed, once interviewees understand their involvement in the research, they can consent to give their right to privacy for the very limited area of the study (Bryman, 2016a, p. 142). However, interviewers should be aware that "*the openness and intimacy of the interview may be seductive and can lead subjects to disclose information they may later regret*" (Kvale, 2007, p. 28). Therefore, the validation of transcripts by interviewees and being able to remove some parts was a way to ensure that we did not go too far in the invasion of privacy.

Finally, the last topic related to ethical questions in qualitative research described by Bryman is the potential for deception. This occurs when the researchers describe to the participant a different goal than the real one. The problem is that, in social research, "*it is rarely feasible or desirable to provide participants with a complete account of what the research is about*" (Bryman, 2016a, p. 143). Indeed, providing too much information about the purpose of the study could lead to some bias in the study. Furthermore, the exact purpose of the research may change during the study. In our case, while the exact aim of the research evolved, the overall purpose, of looking at the barriers and drivers to the use of earth in construction has not changed, avoiding any deception.

The four themes described above highlight the ethical issue related to "*the micro-ethics*" of research respondents' protection (Kvale, 2007, p. 31). However, as explained by Kvale (2007) in the case of interviews, "*macro-ethics concerning the value of the interview-produced knowledge in a larger social context*" (Kvale, 2007, p. 31) must also be considered. In particular, researchers should account for the potential impact of their research on the social context. For instance, this is particularly important

when studying a specific community as the results could affect the social interaction of that community. In this thesis, this question may appear less important. Meanwhile it is believed that the question of integrating the impact of our research should also be considered because it is believed that any scientific research, including technology development, procedures, etc, will have an impact, not necessarily positive, on the social context. This is most visible in applied science such as this research. Concerning the impact on the social context of this study, the reflection on situated knowledges is an answer. Indeed, situating the knowledge developed in Chapter 1 will allow readers to understand the potential socio-political impact, even limited, in earth construction field. This highlights the importance of situated knowledges theory as also being an ethical principle. Besides, the environmental upheaval reminds us that research also has an impact on the environment and care about it should be considered as an ethical issue, as it will be discussed in the following section.

5.3. Ethics and Environment

As explained in the introduction of the thesis, in December 2022, the CNRS ethics committee advised taking into account the environmental impact of research from an ethical perspective (Leclerc et al., 2022). In this report, the committee invited the research community to think about its responsibility in environmental issues from two perspectives: during the practice of the research and on the topics of research and the means to deal with it. This section is dedicated to the first part. Indeed, during the doctoral thesis, and even before the publication of the ethics report, I tried to constantly reflect on the potential environmental impact that I could have during my doctoral thesis. Given my subject and the methods used, the main carbon dioxide emissions came from travel, especially for interviews and conference attendance. For the first, most of the face-to-face interviews were carried out in the same city where the research was conducted, therefore limiting transportation. Otherwise, the other interviews were carried out via video conference or telephone calls to avoid the need to travel. I avoided taking flights during my thesis, which had consequences on my participation in international conferences: those in which I participated were in France and I abandoned my participation to one in Morocco because flying was the only solution to travel (considering the time that I had during that period).

6. Conclusions

The research design of this thesis has been described and positioned among the various literature and methods used to look at the barriers and drivers to the use of earth in construction. The socio-technical approach, within the framework of the design of the building, adopted in this study, was specified as an ontological and epistemological framework for the research (completing the epistemology of situated knowledge already described in introduction). Indeed, the case study will be considered as a

socio-technical system that includes the evolution of the design and the interactions of the stakeholders. Additionally, while analysing the case, observations will be made on technical factors but also political, economic, organisational, and socio-cultural aspects.

The rationales for choosing the qualitative method and selecting a single case study analysis were presented. Highlighting that the strategy to answer the research question is relevant. In-depth information was also provided on the data collected and analysed as part of the study, using different data sources: documents (including meeting minutes, emails, reports, …) from the project and interviews with various stakeholders of the project.

Information on the quality of the research, in terms of validity, reliability and transferability, has been pointed out. Information about the potential biases and risks associated with the research was provided as well as the steps taken by the researcher to counter these issues.

Finally, research ethics were presented, including ethics in research practice (taking care to avoid harm to participants, invasion of privacy, potential deception and obtaining informed consent), but also the ethics related to the environment. In particular, the researcher considers the potential impact (positive or negative) on the climate and the environment as an integral part of research ethics.

Finally, the choice of a single case study methodology is presented as helping to avoid the biases identified in Chapter 2 when following Research Approach 2, which can be summed up as a lack of situating the research. Indeed, it will help to define what means the object, the objective and therefore define what means barriers and drivers in this thesis, along with describing in which context (socio-economic, geographic and stakeholders' perspectives) they occur. This will be the objective of the next Chapter.

4 Situating the case: a definition of what means barriers and drivers in this thesis

Chapter 4 aims at situating the barriers and drivers' study (Chapter 5 and 6) to adapt the conceptual framework into the case study analysis. By doing so, a definition of *barriers* and *drivers* is provided. Firstly, the specificities of the French normative system are highlighted, as the lack of standards has been identified in the literature as a potentially important barrier, which allowed us to understand the central role of control officers. Then, some specificities of the building project are also described including, in particular, the fact that it was part of an urban project and an overall project of five buildings, as this was seen as a facilitating factor for the use of earth in the building studied. Secondly, common and uncommon stakeholders are introduced. Finally, the evolution of technical choices related to the earth in the project is described, bringing to light that the result (being load-bearing rammed earth façades) was not initially planned but instead was the result of a process. The definition of barriers and drivers is given in the conclusion of the Chapter.

Parts of this chapter will be published under:
Pelé-Peltier, A., Goizauskas, J., Under review. Toward a situated understanding of challenges in the design and construction of circular raw earth buildings: the case study of a rammed earth office building in France.

1. Introduction

In Chapter 2, a conceptual framework was proposed for the study of barriers and drivers to the use of earth in construction. This conceptual framework consists in describing the object that faces barriers to attaining an objective, in a specific context and including stakeholders' perspectives. Chapter 3 described the methodology employed for the analysis of barriers and drivers in this thesis as being a single case study analysis. Therefore, it is now necessary to adapt the conceptual framework to the case study. To achieve this, it is then necessary to depict the context of the case, starting with the French normative system and then the building's geographical context and its chronology. Subsequently, the stakeholders' involvement will be outlined. Finally, the "object" and "objective", as introduced in Chapter 2, will be defined to establish a clear understanding of how barriers and drivers will be interpreted in the case study analysis. Finally, an adapted framework will be proposed for further study of barriers and drivers using building case study analysis as a methodology.

This Chapter is therefore major for the understanding of Chapters 5 and 6.

2. A socio-economic and normative contextualisation

Different elements of context are required to situate the barriers and drivers that will be described in the next chapters. Among these elements are the French normative and insurance system and the socio-economic and geographic context in which the case study was built.

2.2. French normative and insurance system

This section will depict the French normative and insurance system, highlighting the interconnections between norms and insurance. First, a rationale for the description of this system will be provided. Then, norms and regulations will be defined, underlining the differences between these terms. The French insurance and the specific guarantees important in this thesis will be pointed out, to subsequently underscores the link with the normative system. Finally, the role played by the control officers in this system will be discussed.

2.2.1. Why describing the normative and insurance system is important?

It was pointed out in Chapter 2 that the absence of codes and standards acts as a barrier to the use of earth in construction, according to the literature (see for instance (Ben-Alon et al., 2020a; Dorado et al., 2022; Kulshreshtha et al., 2020)). As shown in Section 5.2.1. of Chapter 2, this seems particularly true in high-income countries, such as France.

Indeed, the few literatures that have studied the barriers in the French context confirm the above. The report produced by the AsTerre[87] association in 2013 identifies twenty-one barriers to the development of earth as a construction material, in France[88], among which five are related to the lack of standards (AsTerre, 2013). To illustrate, they highlight that:

> *"In a certain number of cases, earth construction solutions have not been implemented, or have not been optimised (from a mechanical or hygro-thermal point of view), for **lack of reference documents on which lean**"[89] (AsTerre, 2013, p. 11)*

As this study is 10 years old, one could say that the question of the standard could be outdated nowadays in France. However, this chapter will highlight that *approved* standards[90] are still lacking in France. In addition, more recent studies have identified a lack of standards in France (Morel et al., 2021b). It was also confirmed by different interviewees, one of them pointing out that this lack of standard should be understood from the perspective of a specific system, the French insurance system:

> *"The problem is that seen from the industry and seen with the glasses we are forced to wear, which are those of construction insurance, **it is a material that has no approved standard**[91]" R04 – Control officer*

Similarly, the AsTerre report describes the question of insurance as linked to the absence of standards. Therefore, to understand the consequences of the lack of standards in the case study, it is necessary to understand how the French normative and insurance system works.

2.2.2. Norm and regulation: definitions

First, to avoid any confusion, it is useful to define the following terms: norm, standard, code, or regulation. Foliente (2000) considers "code" and "regulation" as interchangeable[92] words and provides the following definition:

> *"a building code or regulation is defined as a document used by a local, state, or national government body to control building practice through a set of statements of*

[87] https://www.asterre.org/
[88] It is worth noting that this report is one example of studies falling into the trap of not defining what actually are the perspectives of development considered.
[89] Translated from French to English by the author. Original version: « *Dans un certain nombre de cas, des solutions de construction en terre n'ont pas été mises en œuvre, ou n'ont pas été optimisées (du point de vue mécanique ou hygro-thermique), en raison de l'absence de documents de référence sur lesquels s'appuyer.* »
[90] More information of what mean an "approved" standard in France will be given in the next subsection.
[91] "Approved standard" has been translated by the author from the French "référentiel".
[92] A slight difference exists between code and regulation though. At least in France, codes are legal documents composed of different regulations. Therefore, regulations are parts of codes.

> *"acceptable" minimum requirements. This is typically a legal document." (Foliente, 2000)*

These requirements described in the regulation (or code) are based on "*socio-political and/or community considerations*" (Foliente, 2000), which means they are specific and can differ depending on the context. They can also differ over time, for instance, in France, thermal and environmental regulations have evolved in recent decades (from RT2012[93] to RE2020[94]), modifying the associated requirements. This underlines the importance of also situating the study in time.

The important distinction to keep in mind when comparing regulation and standard is the legal aspects of the former. This means that stakeholders are legally bound to follow regulations, which is not the case for standards. Indeed, Foliente (2000) provides the following definition for building standards:

> *"Buildings standards […] are essentially technical documents that standardize, generally in terms of quality or performance, but sometimes in terms of size or procedure, some activity in relation to building construction." (Foliente, 2000)*

Therefore, while regulations provide legal requirements that must be met, standards (or norms) guide, without an obligation to follow them, how to attain these requirements. Finally, regulations can refer to standards to establish their requirements.

Standards are good practices that are established between groups of professionals based on a consensus as one of the interviewees explained:

> *"Standardisation is about groups of people, with all those interested and able to participate, establishing, based on consensus, good practice in a particular area" R05 – Standards organisation employee*

Standards are then consensus documents of practices, that can be approved by a recognised body (see next section), as defined by Angelino (2019):

> *"Document, approved by a recognised body, that represents the highest expression of professional consensus on technical requirements for the design and assessment of civil and structural engineering works so that they exceed a minimum threshold for safety, serviceability, economy and durability" (Angelino, 2019, p. 36).*

[93] https://www.ecologie.gouv.fr/reglementation-thermique-rt2012
[94] https://www.ecologie.gouv.fr/reglementation-environnementale-re2020

The development of standards is also context-dependent as "*different design loads, design methods, fabrication and construction techniques have evolved based on local tradition and circumstances*" (H. Gulvanessien, 2001). For instance, the Eurocodes are there to harmonize building design methods on a European scale, but national annexes still exist to adjust the Eurocode to certain specificities in the different European countries.

Three levels of norms and regulations exist in the construction sector, related to products; to the conception, through norms or codes of design such as Eurocodes and Thermal regulation; or the implementation (Villain, 2020, p. 404).

2.2.3. French insurance system

The French insurance system for construction is an "all-insurance" system, which distinguishes it from its European neighbours (GT biosourcés action 18c, 2012). Its system is structured by the "*Spinetta*" law of the 4th of January 1978[95]. The law defines four guarantees for the clients, among which two were particularly essential to the understanding of the thesis:

- Ten-year insurance for builders (Architects; Engineers; Construction company) to cover any damage to the building. This insurance is mandatory.
- A "*Dommage-Ouvrage" (D.O.)* insurance, which is mandatory for the clients. The aim of this insurance is to cover the need for financing in the event of damage to the buildings to speed up the repair. The contracting authority's insurers will then seek the builders' insurer to obtain reimbursement through the ten-years insurance. The latter is then necessary to exit the first (GT biosourcés action 18c, 2012).

2.2.4. French normative context: closely related to insurers

The link between insurances and standards will be depicted in this section by highlighting the different level of standards, which will allow to understand the current value of existing earth construction standards from insurers perspective. Finally, a specific technical assessment will be described as it was crucial in the case study.

2.2.4.1. Description of different standards level

In the French construction system, various types of standards exist. These standards are classified according to their importance by the body called "*Agence Qualité Construction*" (AQC), responsible for evaluating and approving the standards created by professionals, through a specific commission

[95] https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000522720

"*Commission Prévention Produits*" (C2P) (Le Moniteur, 2014). This is typically the type of "*recognised body*" introduced by Angelino (2019) in her definition of standards.

This organisation is a public interest association, aiming to assess the pathologies and the recurring and probable incidents for the established or innovative constructions, or to prevent disorders in the building and to improve the quality of the construction according to the evolution of regulations and standards (Villain, 2020, p. 405).

The AQC describes two categories of construction techniques: those which have standards approved by the C2P commission (called "Technique courante"[96] in French) and those which do not have approved standards (called "Technique non-courante"), which does not mean that there is no existing standard.

A summary table is provided by the AQC organism (Figure 4.54), to which one of the interviewees (Third-party controller) refers. This interviewee explains that the more the standard is precise and tested, the more it gains in significance (right to the left on the figure), and the more insurers will have confidence:

R02 – Third-party controller

Sometimes, when some standards are sufficiently tested, they are transformed into standards with greater importance.

Interviewer

Does it gain in value for the insurers?

R02 – Third-party controller

Yes yes, in trust and everything. In precision… Insurers are completely reassured.

---

[96] In English, literal translation could be "Common technique" or "Current technique", however, it has been chosen not to translate it for this thesis. Indeed, misunderstanding could occur around the notion of "common" or "non-common": talking about building heritage, earth construction is quite common in France. Here "common" or "non-common" just refer to the existence of assessed standards, but one could misunderstand that earth construction is not "common" or unusual in France.

For instance, the GDBP[97], which is a standard, as it is a consensus document among earth construction professionals in France, is however not (yet) approved by the C2P commission. Its level of significance is therefore lower compared with other standards that have been approved by the commission. This means, that, although it is still better than nothing for insurers, they still will be less confident in insuring practitioners using this standard.

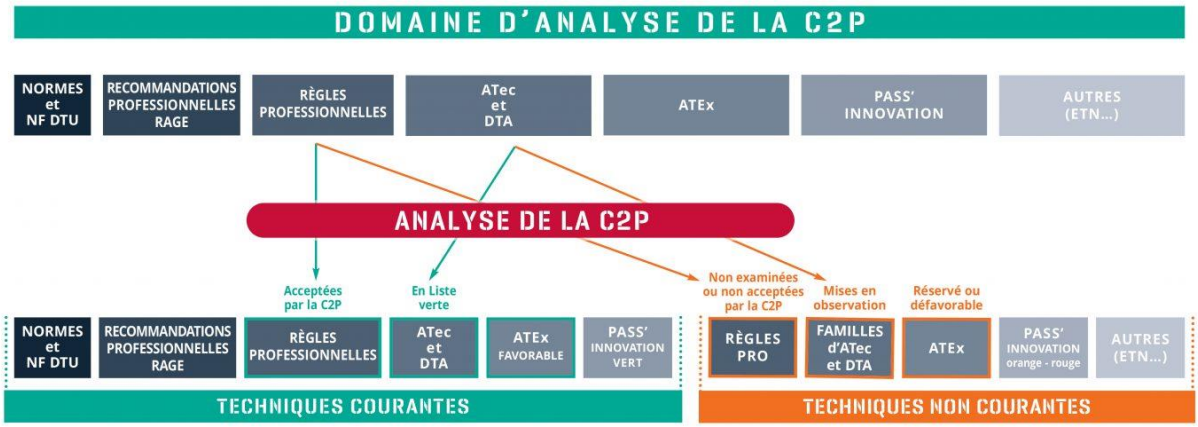


Figure 4.54: figure of the different French standards and the classification between "techniques courantes" and "techniques non-courante" according to the validation of the commission (source: AQC website)

This highlights the role that insurers play in the standard system, as they will preferably provide their services in cases of techniques for which approved standards exist. In practice, stakeholders wishing to use techniques without approved standards must inform their insurers. In this context, depending on their perception of the risk, insurers could ask for price supplements that could dissuade professionals from prescribing or implementing techniques without validated standards (Villain, 2020, p. 406). This was also depicted as a problem in Spain by Delgado and Guerrero (2006) where a similar insurance system exists. Indeed, according to the authors, in the process of assessing building risk before underwriting, insurance companies are assessed through the "*Technical Control Organisations*", which display significant reluctance towards appraising non-conventional materials and construction techniques. This situation presents a major challenge for earth-building initiatives when it comes to obtaining the required insurance coverage (Delgado and Guerrero, 2006). Since this study was published in 2006, it would be interesting to have information about the current situation if it has evolved since then.

2.2.4.2. Existing standards in France on rammed earth

Concerning rammed earth, only one standard exists in France, which is the guide "*Guide des bonnes pratiques de la construction en terre crue: pisé".* This guide was published for the first time in 2018

[97] Available on https://cloud.conf-terrecrue.org/s/BiDHyBrCr3n4iJo

under the direction of ten local and national associations. It exists for other construction techniques including cob, raw earth masonry, earth coating, light earth and wattle and daub. However, this guide has not yet been assessed and approved by the C2P commission. Therefore, rammed earth is still considered a "*technique non-courante*" in France.

This document can be used as a trusted tool among the construction stakeholders because it allows quality to be assessed. It is in any case, an objective stated by the authors of the guide as can be found in the introduction of this guide:

> *"The main objective of the guides **is to contribute to the creation of a relationship of trust between practitioners** - designers, builders, engineers, etc. - and the owners, supervisors, insurers and other stakeholders involved in raw earth structures. - The guides can help them to assess the quality of the construction and the quality of the work."*[98] *("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 4)*

This standard is however seen as insufficient, in particular by control officers. Indeed, the control officer interviewed considers this standard as both insufficiently optimized and scientifically justified:

> *"The available GDBP is quite good, but it's only based on artisans' feedback. This is highly respectable, of course, but it's not optimized enough. [...] We need texts that are scientifically much more established and justified." R04 – Control officer*

It is worth noting here that there are political implications in the creation of new (approved) standards, particularly according to the perspectives of various groups of stakeholders. This will be further discussed in Chapter 6.

2.2.4.3. A specific technical assessment: the ATEx

In the case of techniques without approved standards such as rammed earth, there are still solutions for obtaining specific technical assessments allowing the technique (in specific situations either one specific project, or a specific production process, etc…) to pass from the "*technique non-courante*" to "*technique courante*", and therefore to increase the confidence of the insurers. One of those is called

[98] Translated from French to English by the author. Original version: « L'objectif majeur des guides est de contribuer à créer des rapports de confiance entre les praticiens – concepteurs, bâtisseurs, ingénieurs, etc. -, et les maîtres d'ouvrages, bureaux de contrôle, assureurs et autres professionnels qui sont parties prenantes dans des ouvrages en terre crue. Les guides peuvent les aider à juger de la qualité des réalisations. »

"*Appréciation Technique d'Expérimentation*[99] *(ATEx)*". The ATEx is a technical assessment that can be issued by a French semi-public organisation named CSTB[100], the latter ensuring such certifications among other missions, in particular, the carrying out of research projects. The ATEx is a "*rapid*"[101] technical assessment procedure intended to facilitate the insertion of innovation in current construction (Deshayes, 2012). Different types of ATEx procedures exist addressing different building components. For example, an ATEx procedure dedicated to the assessment of newly manufactured construction products. In that case, once favourable opinions have been provided, the manufacturer of that product will be able to sell it in the condition described in the ATEx report. Another type of ATEx, which is the one of our concerns for our case study, is dedicated to one specific building project. In that case, the ATEx obtained cannot be used in other construction projects.

The ATEx demand is made by a company wishing to innovate or experiment with a technique for which no approved standard is available. This company will draw up a technical document which will be evaluated by a group of experts brought together by the CSTB. This group of experts then gives an opinion either favourable, favourable with reservations, or unfavourable. Once the favourable opinion has been obtained, the technical document is then approved and can help with risk assessment for builders and insurers. Various reasons can explain the need for such a procedure. For instance, If the control officer considers the risk associated with the use of the technique too high:

> *"As a control officer, I have to analyse the risk. Sometimes, I request for an ATEx because the risk is too high" R02 – Third party controller*

Besides, the ATEx procedure can be used to "*reassure*" the different stakeholders involved as it is seen as a trusted tool, as explained by one of the interviewees:

> *"**It is a trusted tool**. When I say we reassure everyone, that's really what it is. Because the innovator has obviously done his work well, so he/she has confidence in himself. But the problem is that all the other stakeholders must also have confidence in him/her. Just on his/her good word, it's not easy. And so, **the role of this third party, the technical evaluator [i.e. the CSTB and the group of experts], who has no conflict of interest, is to validate what the***

[99] That can be translated as "technical assessment of experimentation"
[100] Centre Scientifique et Technique du Bâtiment : have a public service mission to contribute to durable quality and safety in construction (Villain, 2020, p. 408)
[101] Rapid comparing to usual process of creating standards.

> ***innovator says in order to bring confidence*** *in going through the new process." R05 – Standards organisation employee*

Finally, the same interviewee highlighted that it is also used sometimes to solve conflictual situations, while the innovator is therefore required, particularly by the control officer, to proceed to the ATEx procedure:

> *"Due to misunderstandings in the field, the bearers of an innovation may find themselves required to carry out an ATEx." R05 – Standards organisation employee*

Therefore, various factors can account for the necessity of an ATEx. Regardless of the circumstances, it is the control officers who initiate the request, thereby assigning them a central role. This will be further discussed in Chapter 5 in the case study context.

2.2.5. The control officer: a central role in this normative system

The law called "Spinetta" assigns a significant role to the control officer in the design and construction process. The intervention of control officers is mandatory for certain types of buildings or situations defined by the law. They undertake various missions, chosen by the clients. In case of compulsory technical inspection, the minimum missions include an assessment of the robustness of the building, and of the safety of persons, for which they provide advice to the client. While these advisories are not mandatory for insurance companies, they facilitate the insurability of construction projects. Indeed, the advice of the control officers is rooted in an assessment of the risk on which the insurers can base their work to establish their tariffs and contracts. Also, clients are not obliged to follow the advice of the control officers. However, if damages occur due to a disregarded recommendation from control officers, the clients' liability is implicated.

In order to provide their advice, the control officers will base this risk assessment, in particular, on a comparison between the design proposed by the designers and the standards and regulations. Thus, the absence of standards makes it difficult for the control officers to provide their advice, as one of the interviewees highlighted:

> *"**A control officer must provide his/her opinion in relation to a standard, a reference**. The technical controller does not offer an opinion like that, it is not*

> *his/her personal opinion.* ***The result of his/her work is to say: "Yes. The work was carried out following properly a standard". So, if they don't have a standard, in theory, they can't provide an opinion****. They have the right to take the risk, but why would they [the innovation carrier] take the risk for someone else?" R05 – Standards organisation employee*

Consequently, the lack of standards leaves the construction under the control of the control officers who either produce their homemade risk assessment or can call on another body to do so, by means of an ATEx for example. Indeed, a favourable ATEx represents a technical evaluation on which control officers can base their advice. Therefore, due to the lack of standards, the couple standard insurance can represent difficulties for stakeholders willing to use earth materials in construction. In that sense, the lack of standards could be described as a barrier. However, considering it as a barrier can still be discussed and will be in the French context in Chapter 6.

2.3. Some elements of contexts

The description of the normative and insurance system of construction in France was the initial step in outlining the study's context, and it will be useful in discussing factors influencing the use of earth in Chapters 5 and 6. However, a more detailed depiction of the socio-economic context at the project scale is now necessary. This entails considering the building's context and the project timeline.

2.3.1. Building's context

The building studied is a new two-storey office building (Figure 4.55) located in France, resulting from a French private architecture competition. These contextual elements are important as different issues will be raised according to the specific situation of the project, i.e. according to the context (geographical location, new or rehabilitation project, public or private market, stakeholders), according to the program (office, housings, …), and according to the project's scale.

Three particular issues, that will be developed in this section, revealed the importance to describe the specific context of the building: (1) the flexibility afforded by being part of a larger project; (2) the issues related to thermal regulation and labels; (3) the issues related to the storage of earth resource.



Figure 4.55: Recent picture of the building (source: Clement Vergely Architectes)

2.3.1.1. A relatively small building in a large project

The case study was part of a larger construction project involving different buildings with the same project ownership. In total, about 12500 m² were built, for a total of five buildings, among which the case study represented only 1000 m² (i.e. 8 % of the total project in terms of square meters built). Different programmes were included in the global project, such as multifamily housing, office and mixed multifamily housing and office. The case study was, therefore, a small building situated alongside larger structures (Figure 4.56). Various interviewees (including the architect, project owner, thermal and structural engineers) agreed to say that the case study being part of a larger construction project was helpful to achieve it:

> *"We had the chance to build this building in a complex of five buildings" R07 - Architect*

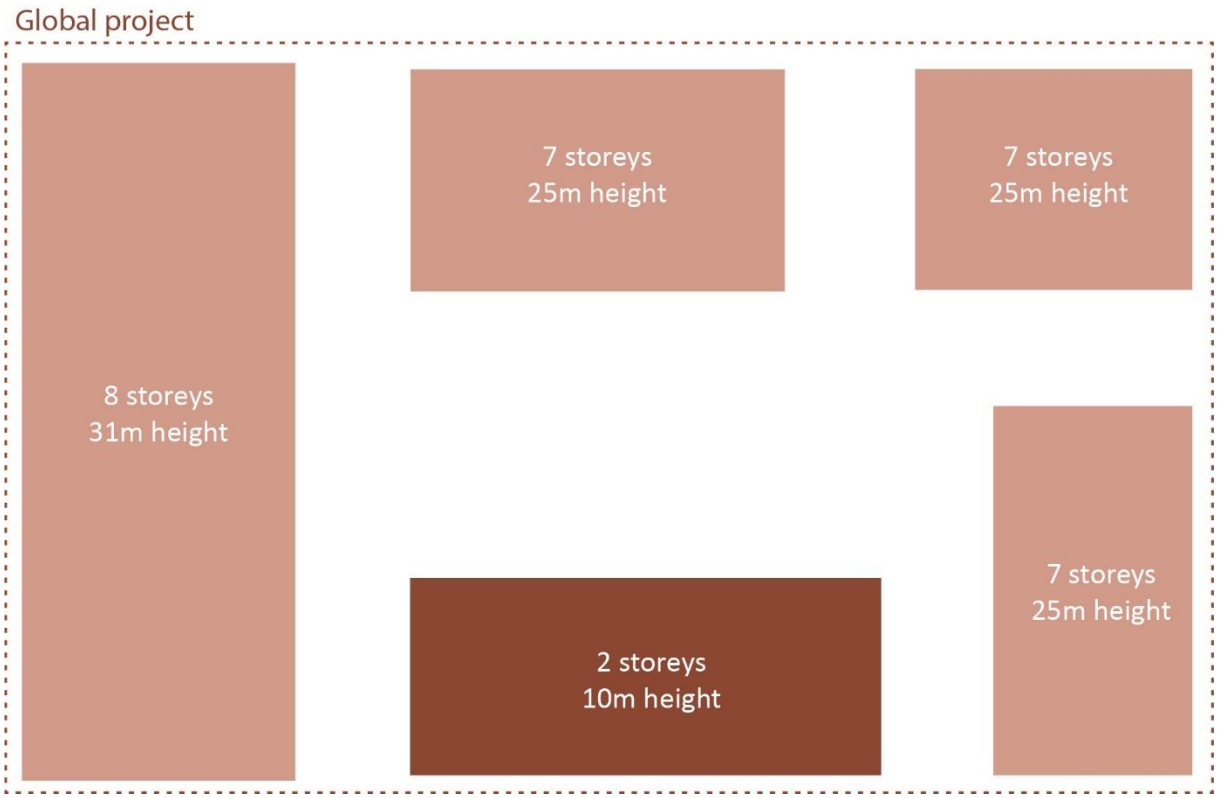


Figure 4.56: Ground plan of the global project at 1:500 scale. The building's case study is in dark brown. (source: author, based on architects plans)

Indeed, it had different advantages. According to the project owner, it offered greater financial and technical resources, enabling the absorption of any additional costs, as well as increased flexibility in the schedule to avoid any detrimental delays. This was confirmed by other interviewees:

> *"It was 1000m² in a much larger block and so there was the possibility of a* ***form of absorption [of costs]****, of contingencies.* ***And even for the construction schedule, which allowed the schedule for this building*** *[case study]* ***to be shifted****. Because, in any case, the planning for the whole block lasted much longer.* ***And that was a big flexibility****." R06 – Thermal engineer*

> *"The smaller the operation, the fewer resources we have to implement innovations. On the contrary, on an operation like [name of the complex of buildings], which is quite large (more than 12,000 m²),* ***we have more technical and financial means to do things****" R03 – Project owner*

In addition to allowing greater flexibility in the construction and for the project owner, it also permitted greater financial flexibility for the designers. On the one hand, the scale of the project was allowed to

be less profitable for the clients because it represented only a small part of the overall envelope. This provided more freedom to experiment in the design phase as one interviewee pointed out:

> *"There was an intention to have another scale,* ***to experiment, to have something more atypical and where the project owner gave us more freedom*** *in the sense that* ***we could have something a little less profitable****, which would not burden the operation as a whole." R08 – Structural engineer*

On the other hand, it also permitted more financial flexibility for the designers, as the architects highlighted. Indeed, they were engaged on the entire project which allowed them to defer fees from one building project to another. Finally, as one interviewee pointed out, the case study benefited from the skills of an overall project design team:

> *"It benefited from the project management of a much larger block. So normally* ***more structured, less amateurish design offices****." R06 – Thermal engineer*

Therefore, this section highlights the impact of the building context on the barriers and drivers to achieve the building project, illustrated by one of the interviewees as follows:

> *"If we had done only this building [the case study], I think it would have been much more difficult" R07 – Architect*

Indeed, it was observed in the literature that extra costs (Ben-Alon et al., 2020a; Kulshreshtha et al., 2020; Owino et al., 2014b; Zami and Lee, 2011c) and more specifically unexpected costs (Ben-Alon et al., 2020a) seem major barriers. However, in the case study, it did not appear as a main obstacle (although issues related to costs will be discussed in Chapter 5 section 4.3., in particular in the relationship between masons and project owners), thanks to the financial flexibility offered by the overall project.

2.3.1.2. Specific thermal and environmental labels targeted

Additionally, to being part of a larger construction project, the case study was also part of the second phase of an urban plan (in France, a generic name for such an urban plan is ZAC[102]). The latter corresponds to the development of buildings on a former industrial site located in an urban area close to the city centre for a future dense area, aiming to accommodate four thousand new inhabitants on 35,000 m².

This context is accompanied by intentions on the thermal and environmental requirements, wanted by the developer of the area and affecting the different buildings of the entire project. In particular, the case study was subjected to two regulations: BREEAM®[103] and HQE®[104]. Contrary to the flexibility allowed by the complex of five buildings, these regulations were considered by one of the interviewees as a complicating factor:

> *"In ZAC 2, they wanted to introduce the issue of the carbon content of building solutions. But this was new, and they did not want to give up on energy. [...] There were coefficients on the quality of the thermal envelope and its level of insulation that were really firm. [...]* ***Among the factors of complexity, there was this regulatory framework****." R06 – Thermal engineer*

While the first phase of urban planning focused on energy consumption with higher requirements than those conventional at that time, the second phase introduced a reflection on the carbon intensity of the building materials used. The designers, therefore, addressed this double constraint for the building project.

2.3.1.3. Geographical situation: opportunities and constraints relative to the earth resource

The geographical situation of the project brought opportunities and constraints about the earth resource, relative to the earth sourcing and then to its storage. The material sourcing will be discussed in Chapter 6 section 4.1 as it is a key step in the approach adopted for the design and construction of the building.

[102] ZAC Zone d'Aménagement Concertée [Concerted development area]
[103] BREEAM® (BRE Environmental Assessment Method) is an environmental performance assessment method developed by BRE (Building Research Establishment), a private research UK company on building's research. https://bregroup.com/
[104] HQE® (Haute Qualité Environnementale [High Environmental Quality]) is a French certification or label that is supposed to ensure a high level of environmental quality. https://www.hqegbc.org/. See (Sánchez Cordero et al., 2019) for a comparison between the different environmental certifications in Europe.

In an urban context, as was the case for the building studied, the storage of earth can raise an issue if earth is implemented on site. This storage issue was already described by H. Gasnier as a constraint for the site (Gasnier, 2019, p. 58). This constraint was confirmed by the interviewed mason, in particular in urban areas, emphasizing however that it was not specifically true for earthen construction, but also for other materials when there is a need for storage. The construction site was in an urban area, but at that time was still being reconfigured in urban planning (different buildings had already been demolished), so it was possible to find storage places near the construction site. However, it required negotiation with the urban planners.

2.3.2. Chronology of the building project and the study focus

Another element of context useful to detail for the thesis is the chronology of the project and in particular, the section studied for the research.

As discussed in Chapter 3, the focus was on the design process and construction phases and the data was analysed from competition award until building delivery. This includes different phases of design and construction: detailed design, application for building permits, technical design, tender file procurement process assistance, VISA execution studies, and construction phase. For the concordance between the French phasing system of construction and the one proposed by the Royal Institute of British Architects (RIBA), see (Charef, 2019, p. 105).

The detailed design[105] occurred between January 2016 and October 2016, ending with the building permit application. In this phase, the last details of the design should be developed including the choice of materials and precisions on the technical choices. The cost of the entire project is then finalised (Bâtiments, 2012).

Technical design[106] begins with the acceptance of the building permit application and aims to establish the detailed plans of the building ensuring a good understanding of all the specifications of this building. In the case study, this phase began in November 2016 and ended in April 2017 with the start of assistance in the procurement process[107] and the production of the tender file[108], drawn up in December 2017. After this, the project owner chooses the contractors for the construction following the advice of the design team.

While the first construction meeting for the overall project took place in February 2018, the service order to launch the execution studies for the rammed earth structure was delivered in March 2018.

[105] Acronym *APD* in French for *Avant-Projet Définitif*
[106] Acronym *PRO* in French meaning *Etudes de Projet*
[107] Acronym *ACT* in French for *Assistance aux contrats de travaux*
[108] Acronym *DCE* in French for *Dossier de consultation des entreprises*

The purpose of these execution studies is the technical implementation of the construction project and aims at establishing the plans and calculation notes intended for the contractors that will build the project. The execution is then monitored by the design team to check the consistency with the previously established plans.

Finally, the construction of the building took place from June 2018 until the delivery of the building, first with reservations in November 2020 and then final delivery in January 2021. During the construction phase, two periods of rammed earth construction took place[109]: from July 2018 to mid-October 2018, and from April 2019 to mid-august 2019.

All dates in the case study were established based on the available documentation analysed including emails (See appendix D).

2.4. Conclusion of the section

This section highlighted the need to contextualise the case study in the French normative context. Particularly, as there is a lack of approved standard (which mean consensus document among professionals that have been approved by a standards body) for rammed earth construction, it was necessary to describe the relation between insurances and standards. Indeed, the more approved the standard is, the more insurers would be reassured. This allowed to highlight the crucial role played by control officers when their mission is to provide an opinion on the design in comparison with existing standards or regulations. This opinion is helpful for project owners to obtain their insurance, or at least to not have supplementary insurances costs. However, when standards are lacking, control officers can require what is called an ATEx, which is a relatively quick process to obtain a specific standard by approval from a commission of standards experts. This is major as an ATEx procedure was required by the control officers in the case study.

Finally, some other elements of context influencing barriers and drivers were described, including the relatively small size of the building being part of a larger project. This offered schedule flexibility, greater financial and technical resources, enabling the absorption of any additional costs both for project owners and designers. The targeted labels, that represented a constraint for the rammed earth will be described in Chapter 5, and the geographical situation offering storage opportunities were also described. In the end, the chronology was detailed for better understanding and is reported in a timeline in Appendix D.

[109] Reasons for this will be explicated later.

Now that the context has been underscored, following the concept framework developed in Chapter 2, it is necessary to describe the stakeholders involved in the case study.

3. Stakeholders' involvement

Another important factor to consider when studying barriers and drivers is the stakeholder's perspective, as outlined in Chapter 2. Therefore, this section aims to describe the stakeholders involved in the case study concerning the use of earth. The common[110] stakeholders will be described, including the initial design team (architects and engineers), the project owners, the control officers, the urban planners, highlighting the specificities of the project. Then, the uncommon stakeholders will also be described, including stakeholders who are not usually involved in construction projects (such as academics) but also stakeholders who were involved at unusual phases in the design process (masons).

It is worth noting that the construction of buildings is the result of an interaction between many stakeholders[111]. All of these will not be presented in this section as the focus is made on those related to the use of earth in the case study. Moreover, for the study, a particular emphasis was placed on the design process (although some lighting will be made on the construction), therefore certain stakeholders have been excluded even if they could have been linked in some way to the use of earth at a given time (for instance the carpenter or the site manager). Finally, the choice of the stakeholders to be mentioned was made according to their occurrence in the analysis of the emails. This explains why some stakeholders were excluded, such as the economists for example, as their presence in the emails is quite limited, which does not mean that they do not play an important role. The reader should therefore be aware that this might constitute a potential bias. Throughout the thesis, when mentioning the structures involved in the case study, the plural will be used. Indeed, most of times more than one employee of those were involved. Moreover, this help to use a form of inclusive writing. The singular form will only be used when mentioning the interviewees. Inclusive writing will be respected as well as a way to strenghten anonymity of the interviewees. Finally, the name of the structures is mentioned only when the agreement has been provided.

3.1. Common stakeholders involved in the design phase

3.1.1. Initial design team

For the competition, the project owners had assembled a project team for the global project:

[110] Common in term of stakeholders usually involved for this type of buildings.
[111] see for example Charef (2019) page 227 for a description of different stakeholders with their different roles from a circular economy perspective.

> *"The project owner has brought together a complete project management team, with their advisors, both a team that shows high and joined-up skills for the operation and then to meet their ambitions. So, there was the classic team. An architect... There were even two, a Swiss architect and a local one. In addition, there was a fluid design office and an environmental design office. A construction economist and they had called on two structural design offices." R08 – Structural engineer*

The design team was composed by the architects, and structural, thermal, and environment engineers.

3.1.1.1. Architects

As described by respondent 08, two architectural firms were involved in the overall project. They worked together on the design of the complex for the competition, however, only the local architectural agency worked specifically on the case study, having a complete mission as coordinator:

> *"In any case, we had a complete mission on this project, so we were, in a way, the trustee and we were supposed to gather everyone behind us to put ourselves in order." R07 - Architect*

Therefore, when referring to the architects in this thesis, one should understand the local architectural firm, namely Clement Vergely Architects[112], that worked on the case study.

3.1.1.2. Structural engineers

Two structural design offices were brought together to work on the case study. One specialized in timber and was responsible for calculating the timber structure of the building, and the other, a structural design office working on all types of materials, namely Batiserf[113], had the mission of working on the earth façades and concrete basements.

In the case study, it is above all the structural engineers working on the earth façades that interest us. Moreover, other sections will highlight that they played a growing and important role during the design of the building. Therefore, they will be labelled as "structural engineers" throughout this thesis, while the other structural design office will be notified as "timber structural engineers" when necessary.

[112] http://www.vergelyarchitectes.com/
[113] https://batiserf.com/

The structural engineers (SE) were commissioned in the design phase for the calculation of the façade but did not have a site monitoring mission for these façades. However, they were hired as an execution design office for the masons. They were therefore involved throughout the entire timeline of the project.

3.1.1.3. Thermal and environmental engineers

Complementing the design team, thermal and environmental engineers (TE), namely Etamine[114], were involved from the start, with the mission of enabling the project to meet the requirements (thermal and environmental) required by the urban planner through regulations and labels described in section 2.2.1.2.

> *"Our reason for being on the project was to ensure that the project met the ambitious specifications of the developer. That's why we were called in." R06 – Thermal engineer*

Other members of the design team were depicted in the quotations of respondent 08, including the economist and the fluid engineers. However, they were of less interest from the perspective of focusing on earth construction, at least in the specific context of the case study.

3.1.2. Project owners and clients

The project owner was a developer, being the first client, aiming to coordinate the design and construction within budget and time to then sell it to other clients who could be the end-users of the building. They displayed a desire to build virtuous buildings, in terms of the environment.

> *"[Name of the project owner structure] is a national developer. It is not a major developer, but it does have 250 employees. We are located in Paris, Lyon, Marseille, Annecy and Nice... we try to be virtuous developers [...] We know that the impact of construction is quite enormous in terms of overall carbon weight, and so the idea is to see what we can do to reduce the impact of new constructions in particular" R04 – Project owner*

[114] https://www.etamine.coop/

Some authors have underlined the importance of the client, particularly in the choice of structural materials. For instance, through eight exploratory interviews and four focus groups among Oregon construction professionals (including architects, engineers, contractors and developers), Griffin et al. (2010) highlighted that, as clients have the most financial interest in the building project, "*they are also the most risk-averse of all the involved parties*" (Griffin et al., 2010). In this context, they highlighted the importance of involving clients as advocates for the use of new structural materials.

3.1.3. The control officers

The role of the control officers, in general, has already been pointed out in the French insurance and normative system in section 2.1.5. In the case study, the control officers were involved upfront in the competition as advisors to the project owners.

3.1.4. Urban planners

Finally, on another scale, the urban planners influenced the project in particular through the thermal and environmental requirements imposed to the design team.

3.2. Uncommon stakeholders involved in the design phase

Additionally to the common stakeholders involved in the design of the case study, uncommon ones were also involved, related to the use of earth in the building: the earth advisors and the third-party control officers.

3.2.1. Earth advisors – the extended design team

The introduction of earth advisors in the design and construction of an earth building was already recommended in the literature in particular to compensate for the lack of standards and norms (Van der Linden et al., 2019b). Various earth material advisors were involved during the design of the case study: academics and masons.

3.2.1.1. Academics

Two teams of academics of two distinct structures were introduced in the design of the building by various stakeholders. On one hand, the structural engineers took the initiative of contacting academics (that will be called Academics A, or simply Academics, for the study, and are researcher in the laboratory GCD-LTDS at ENTPE[115]), the latter being considered scientific experts in the field of earth construction.

[115] https://www.entpe.fr/laboratoire-de-tribologie-et-de-dynamique-des-systemes-ltds

> *"And it was [head of the structural engineers' office]'s initiative to get the support of people who had the greatest expertise in these areas [earth construction], in addition to the skills of the craftsmen. Because they have been working and researching for a long time. It was the laboratory of [name of the structure]." R08 – Structural engineer*

Although the office of the structural engineer has been used to call upon the services of the laboratories (for lab testing in particular), they were not used to call upon the academic laboratories. They contacted them apparently to compensate for a lack of knowledge of earth construction.

> *"Generally, we do it [call for support from academics**] only if we feel a bit unsure** or "light" from a technical perspective" R08 – Structural engineer*

Academics A was therefore involved from the first phase of the design process after winning the competition until the delivery of the building, with a timely but consistent dialogue between them and the structural engineers, thermal engineers, masons and architects.

On the other hand, another laboratory (that will be called Academics B) was contacted for its expertise in earthen construction at the same time when the other academics became involved. They were only involved for a short time, until the end of the first phase of the scheme design. The data analysis did not enable to say by who they were first contacted.

3.2.1.2. Masons

Finally, to complement the extended design team, masons, from the structure "Le pisé"[116], were involved early in the design as advisors. Considered "true experts" on rammed earth by the structural engineers, they were introduced by academics A.

> *« Well, the true experts, it was [name of on the masons] when he arrived in the project. But with technical, craft, and implementation skills." R08 – Structural engineer*

[116] http://www.construction-pise.fr/

The architect noticed that working with masons during the design phase was unusual, whereas they were usually involved during the construction phase.

> *"Is it something that you are used to working with masons in the design phase?"*
>
> *Architects:*
>
> *"We try. **But it is really not common** because, when you design a project it is generally done without the contractors and **it is at the tender file phase that we meet them**. Sometimes, for a project like this [the case study], we need the contractor earlier. Often, it is almost impossible because it is not allowed to work with one exclusive contractor." R07 – Architect*

In addition, the masons were used to intervene in the design phase of small housing projects, for which they were accustomed to doing design-build for individuals.

The involvement of masons (or more broadly the contractors) early in the design phase is indeed sometimes seen as a driver of the use of earth in construction in the literature (Morel et al., 2021b).

3.2.2. Third-party control officers

Finally, different third-party control was made necessary in the case study. When an ATEx procedure (described in section 2.1.4.3.) was requested by the control officers, the related control organism was called, playing the role of a third-party control such as described in section 2.1.4.3. It will be called "standards organisation" for this thesis.

Besides, another third-party control, namely APAVE[117], was requested later in the project to control the production of rammed earth during the construction phase. This mission was untrusted to another control officer, from a distinct company to those already involved in the case study. The third-party controller highlighted that it is an unusual mission in the construction industry:

> *"So you say that this mission is very unusual … ?"*

[117] https://france.apave.com/

R02 – Third-party control officer:

"Well yes, I'm a control officer for 20 years and it is the first time."

3.3. Conclusion of the section

This section described the different stakeholders involved in the project and that were important at some point for the understanding of the Chapter 5. They were categorized in two groups: common stakeholders that include architects, structural engineers, thermal and environmental engineers, project owners, control officers and urban planners; and uncommon stakeholders including the involvement early in the design of academics and masons as earth advisors, and the involvement of a third-party control officer during a part of the construction phase. The stakeholders involved at specific time are depicted in Appendix D. A point means the entrance of the stakeholders in the project. if there is no line related, it means they were involved during all the rest of the project. The others were not represented to a matter of clarity of the Figure, as they were involved all the time in the project.

4. Defining the focus of the study on the wall element

This section aims to define the object of study being the façade element of the case study. The first part will describe the element as an evolving one while the second part will highlight the different evolutions of the façade element that will be placed in the timeline of the project.

4.1. Evolving element of wall

This study aims to examine the barriers and drivers to the use of earth in the case study. As recalled in Chapter 3, the production of the building is the result of a complex design process, which would be difficult to analyse as a whole. Thus, for this study it was decided to focus on a façade element, ultimately made up of load-bearing rammed earth, to concentrate on the issues closely related to the use of the earth. Making this choice introduces a bias in the analysis by hiding certain elements that were not directly linked to the use of earth but were linked to the building as a whole. For instance, the seismic aspects will not be detailed in this thesis. Indeed, in the case study, the problem of supporting the seismic load for the rammed earth has been diverted by designing a timber structure composed of a sufficiently rigid central core, to bear this load. The timber structure, therefore, supports the horizontal loads instead of the façade.

To understand the constraints under which the wall element evolved until it reaches its final form, it is important to highlight the various technical decisions that were made by the design team throughout the building project's chronology. Indeed, as A. Yaneva proposes in her book "*The Making of a Building:*

a pragmatist approach to Architecture", to appreciate the complexity of the design process, buildings cannot be investigated only "*after the fact of their construction*" (Yaneva, 2009, p. 3). It is therefore important to situate this evolving element of the wall in time by describing the result (part of the finished building), and the element planned for the competition, and to highlight the different evolutions.

One should be aware that, as the focus of the study is on the load-bearing elements of the superstructure of the building, certain parts have been left out in this thesis, for instance, the wooden carpentry or the foundations. Therefore, the study of the interaction between earth material and other materials, in particular wooden carpentry, will be limited although this has already been highlighted as a potential problem in the literature, in particular in the case of interaction between concrete reinforcement and non-adjuvanted adobe (Hurol et al., 2015). Figure 4.57 represents the façade element extracted from the building, considered for the study. The selection of the element (selection screen) has been made to facilitate the representation of the different points discussed in the next Chapter.

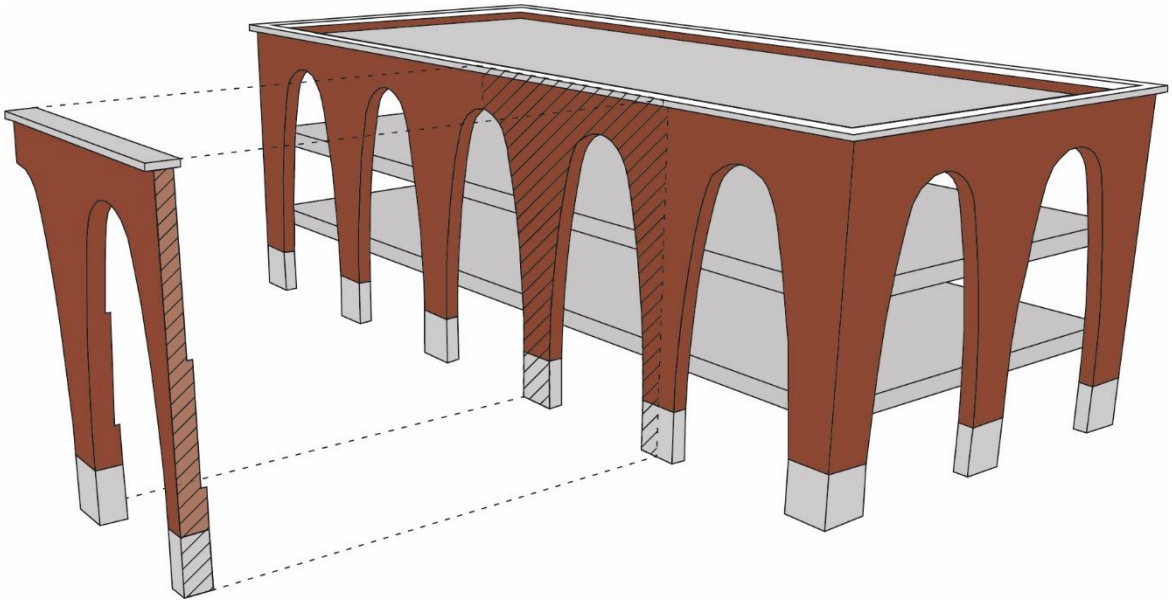


Figure 4.57: Schematic representation of the building and the extracted element of wall considered for the study (source: author)

4.2. The final element of a wall

The final wall element studied, as shown schematically in Figure 4.58, is composed of a load-bearing rammed earth façade in a shape of an arc. Blocks of rammed earth were prefabricated on-site and then assembled with earth mortars (composed of the fines of the earth) by the masons (Figure 4.59). The thickness of the wall decreases from 80 cm to 50 cm between the ground floor and the second floor. The floors, made of timber structure, lay on the rammed earth façade at the junction between the different thicknesses of the wall, with a steel assembly. To protect the rammed earth walls from

water, these are covered with stone elements with a roof overhang, avoiding direct rain, and rest on a stone basement about 1.60 m high. Finally, the corners of the building, as well as the intrados of the arches, are bevelled with chamfers.

Although this corresponds to the delivered building, it should be noted that this wall element was not initially designed like this.

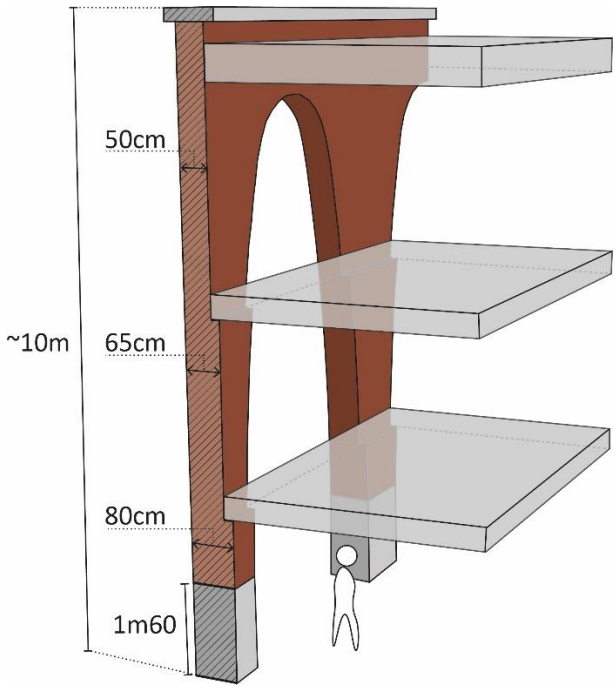


Figure 4.58: Schematic representation of the finished element of the wall. For clarity of the scheme, not all the elements are represented (in particular the wooden carpentries), keeping a focus on the rammed earth façades. (Source: author)



Figure 4.59: Pictures showing the assembled prefabricated blocks of an element of wall (source: author)

4.3. An undefined wall element at the competition

At the end of the competition, the analysis of the documents and interviews highlights that some elements remained unclear (or non-consensual between stakeholders) in the design of this façade element, particularly concerning the material resource, the constructive technics and the load-bearing capacity of the earth façade.

Regarding the material, at the time of the competition, a lime adjuvantation[118] of the material was considered by the structural design engineers, in particular, to reduce the sensitivity to water. In a note from the competition files written by the structural engineers, it can be read:

> *"For the success and durability of the arches is to **use lime-stabilised rammed earth**, to limit the sensitivity of the material to the action of water, to increase its compressive strength and finally to guarantee its durability against erosion" Translated from the competition note of the structural design office*

However, this adjuvantation was quickly abandoned after the masons joined the design team because they highlighted a risk that lime adjuvantation could represent in the event of frost.

Most of the stakeholders agree that the earth technique (i.e. the way earth material would be implemented, see Figure 0.15 in the introduction for the different earth technics) was defined as rammed earth, proposed by the architects, since the competition:

> *"We started in rammed earth at the beginning of the competition, yes." R03 – Project owner*
>
> *"We proposed this solution, the rammed earth, in the competition" R07 – Architect*
>
> *"From the competition, it was rammed earth" R08 – Structural engineer*

However, for some stakeholders, the technique was not yet well defined as rammed earth:

[118] In scientific literature, the word "stabilization" is generally used to refer to cement or lime adjuvantation. However, the authors consider that it creates confusion by distinguishing a "stabilized" and "unstabilized" form of earth material. In this chapter, the authors will prefer the word "adjuvantation" referring to the addition of an external material (commonly cement or lime) not being naturally present into the earth.

> *"For you, at the time of the competition, was it raw earth cladding, rammed earth or something else?*
>
> *R06 – Thermal engineer:*
>
> ***It was not well defined**. We were deliberately evasive on this issue. The architects wanted an rammed earth aesthetic. But from a space point of view, combined with the wooden façade, we knew that it was not buildable. Even the structural design office said so. For me, **this question was unresolved at the time of the competition.**" R06 – Thermal engineer*

Moreover, as the last quotation pointed out, the load-bearing capacity (i.e. the choice of making the earth façade load-bearing the building or only itself) was not yet agreed upon by all stakeholders. Indeed, at the time of the competition, the documents reveal a load-bearing timber structure carrying the façades of the building (See Figure 4.61 for an extract of the plans of the competition and Figure 4.60 for a schematic representation of the structure of the wall element at the time of the competition). Therefore, the rammed earth was more like a cladding at that time. However, it was clear to the structural engineers that this rammed earth had to be load-bearing:

> ***"In our minds, it was obviously load-bearing rammed earth, because we can't imagine that it could be otherwise**. It wasn't as clear or explicit in the details or the rendering. But so, it was wooden floors and load-bearing rammed earth façades." R08 – Structural engineer*

This choice to remain vague on the load-bearing capacity and technical choices for the façade appeared as a strategy to avoid possible reluctance from the project owners, in order to win the competition, as underlined by the structural engineer interviewed:

> *"I think that we had made a rather political and reassuring answer to say, at that stage, that we were doing rammed earth. But **we didn't want to fight over whether it would necessarily be successful or not, because that wasn't***

the point. The aim was to win the operation and to have the chance to continue. *" R08, Structural Engineer*

Therefore, this section highlights that different evolutions and precision have been adopted for this wall element. To improve understanding, these evolutions can be placed in the project timeline.

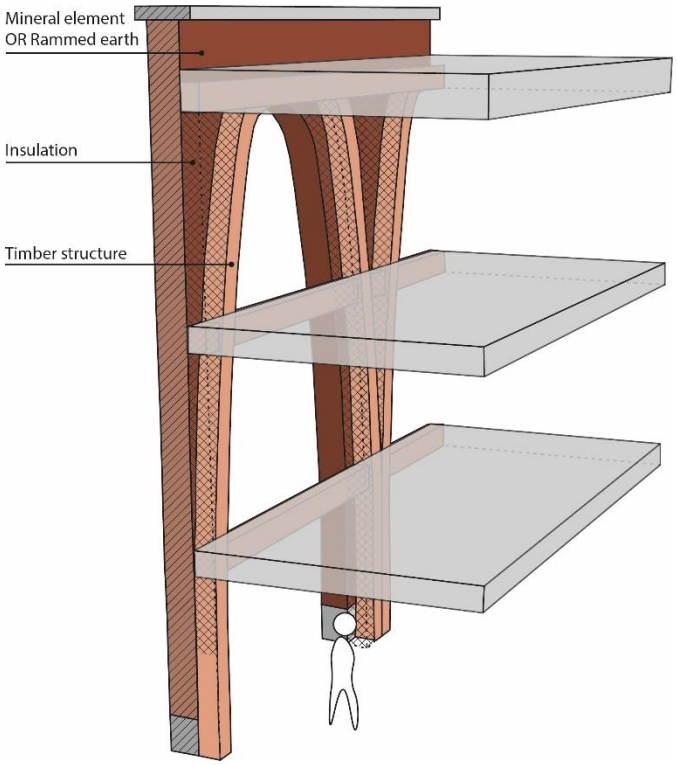
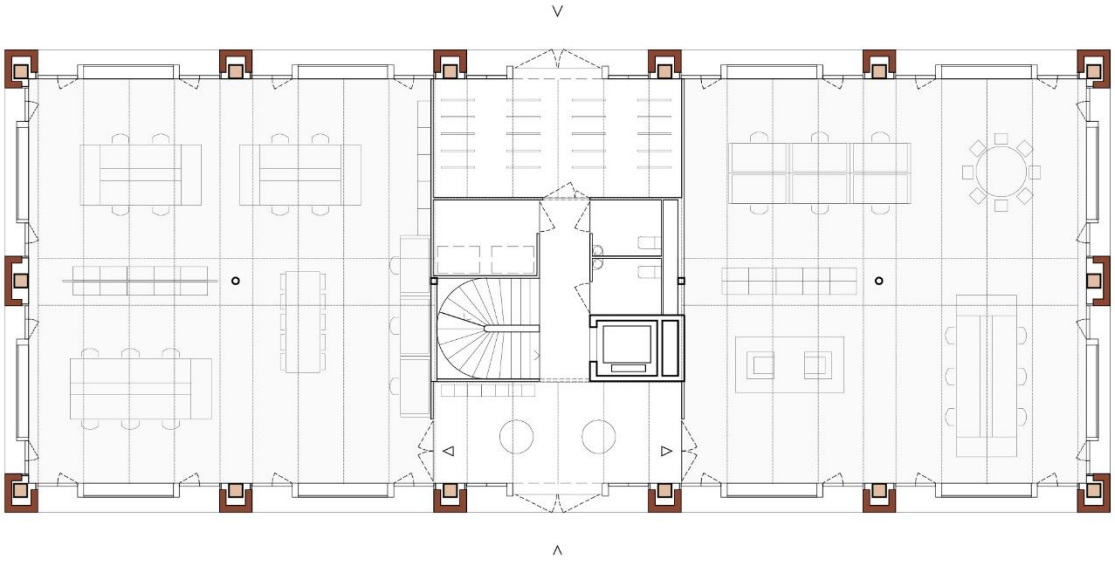
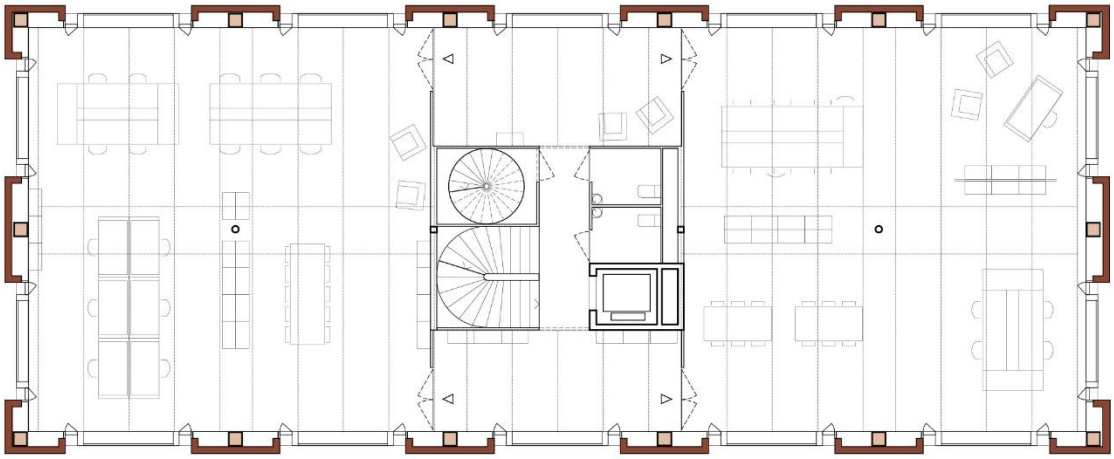


Figure 4.60: Schematic representation of the element of wall at competition time, composed of a timber structure, an insulation, and façade composed of mineral elements or rammed earth according to the stakeholders and the different documents (source: author)



Ground floor's plan 1/200



Second storey's plan 1/200

Earth facades

Timber structure

Figure 4.61: Plans extracted from the architects' files of the competition (©Clement Vergely Architectes) - Highlights in colour were added by the author to bring to light earth façades and the timber structure.

4.4. Timeline of the evolution of the wall element

Various technical elements of the façade have therefore evolved or have been detailed between the competition and the delivery of the building. Various technical decisions were taken throughout the project chronology, among them, some were taken upstream, during the detailed design phase, corresponding to the common building design process (Bâtiments, 2012): such as the batter of the wall, the height of the basement, the brushing for the erosion, or the choice not to use adjuvants in the earth material. Others were reported in this phase but the decision taken later in the project, such as the chamfers (See Figure 4.62 [plans extracted from tender files] where the chamfers are represented on the plans in the intrados of the arches, but not yet in the corners of the building). Furthermore, the decision to prefabricate the blocks was taken during the competition. During the detailed design phase, the use of rammed earth was also questioned, with the possibility to replace it with poured earth associated with the timber structure planned during the competition, but this was abandoned after the filing of the building permit. After that, other important technical choices were made: in particular, a controversy over the insulation of the rammed earth lasted until this insulation was abandoned during the construction phase. Moreover, the load-bearing capacity of rammed earth was constantly subject to debate, in particular by the control officer, until the delivery of the building. Indeed, in the tender documents, a timber structure is still observable on the plans (See Figure 4.62 and Figure 4.*63* for a schematic representation with the timber pillars). In addition, the ATEx report was established for load-bearing rammed earth, and then precautionary posts were envisaged but ultimately not installed. Figure 4.64 represents the evolution of the main technical choices made during the chronology of the project.

The wall element therefore evolved in the design according to the different stakeholders until it stabilized into a load-bearing rammed earth façade solution adopted and built, reaching a kind of consensus among the stakeholders. Consensus must be understood here as the achievement of the process to have all the stakeholders accept the final technical solution that is built. This was a long process though, as it has been underscored in this section. This was confirmed by one of the architects in a press article:

> *"The control and insurance offices are not used to this. It is the rammed earth that is load-bearing, there is no cement.* ***It took between twelve and eighteen months to get everyone to accept this project."***[119]

[119] Translated from French to English by the author. Original version: « Les bureaux de contrôle et d'assurance n'ont pas l'habitude. C'est le pisé qui est porteur, il n'y a pas de ciment. Il a fallu entre douze et dix-huit mois pour faire accepter ce projet à tout le monde ». Source : Gossart, D., 2019. 2e arrondissement : Après les cubes design, la Confluence se met à la

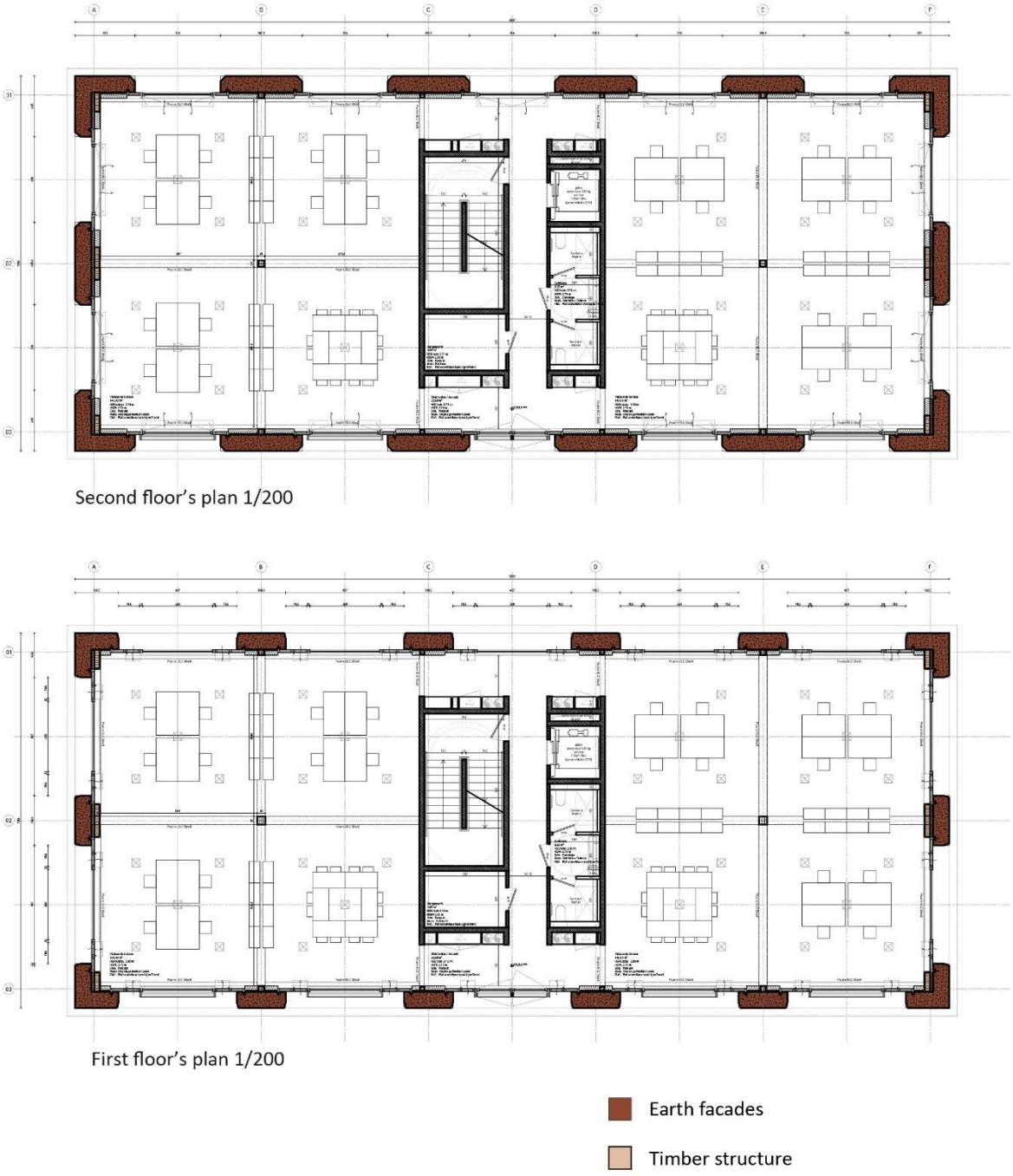


Figure 4.62: Plans extracted from the tender files (© Clément Vergely Architectes) - The highlights in colour have been added by the author to bring to light the earth façades and the timber structure.

terre crue [WWW Document]. Tribune de Lyon. URL https://tribunedelyon.fr/urbanisme-immobilier/2e-arrondissement-apres-les-cubes-design-la-confluence-se-met-a-la-terre-crue/ (accessed 5.12.23).

The next chapter will show that the consensus is the result of collaborations and tensions between stakeholders and of socio-technical considerations and normative constraints.

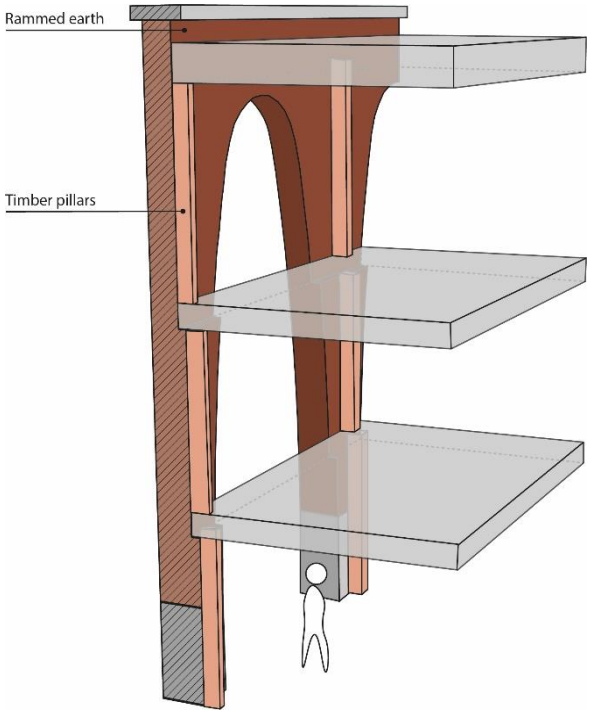


Figure 4.63: Schematic representation of the wall element representing the timber pillars(source: author)

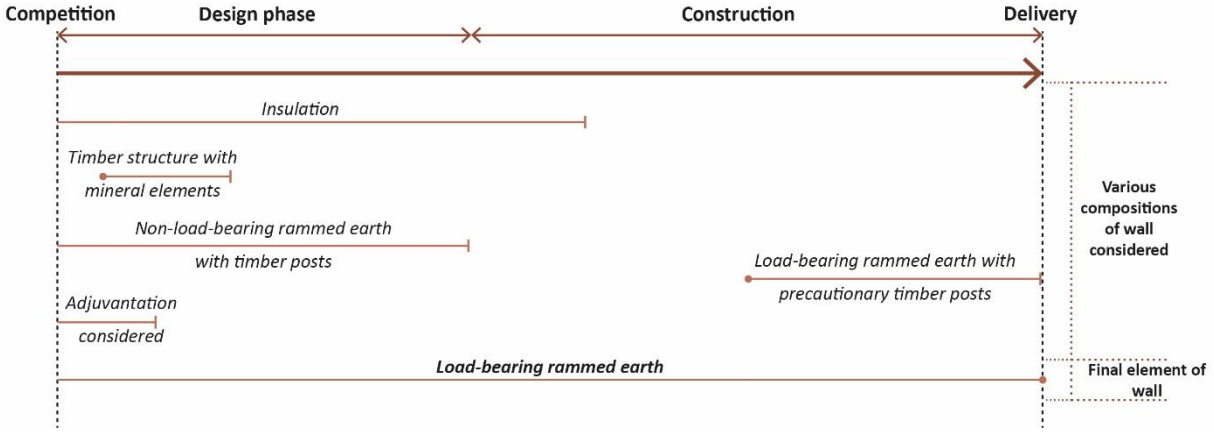


Figure 4.64: Schematic representation of the different technical solutions considered during the design and construction

4.5. Conclusion of the section

This section defined the object as the evolving conceptual[120] element of wall and the objective as the load-bearing rammed earth façades eventually realized. It should therefore be noted that this

[120] Conceptual captures the idea that the design is still in the process of development and may change.

objective was not known by the stakeholders while the conceptual element of wall was evolving. Two main categories of evolution will be interesting to describe in the next Chapter: (1) one related to the load-bearing capacity of the rammed earth walls, as it has been shown in this section that different solutions were considered. (2) And one associated to the design of this element of wall implying different technical choices including: removing the insulation and treating the risk of erosion.

5. Adapting the framework to case study analysis and provide a definition of barriers and drivers.

Following the conceptual framework developed in Chapter 2 (Figure 4.65), this chapter describes important parameters relative to the context, the stakeholders, the object and the objective considered. This will be useful both for understanding the next chapters (5 and 6) and to situate the case and the approach of barriers and drivers analysis.

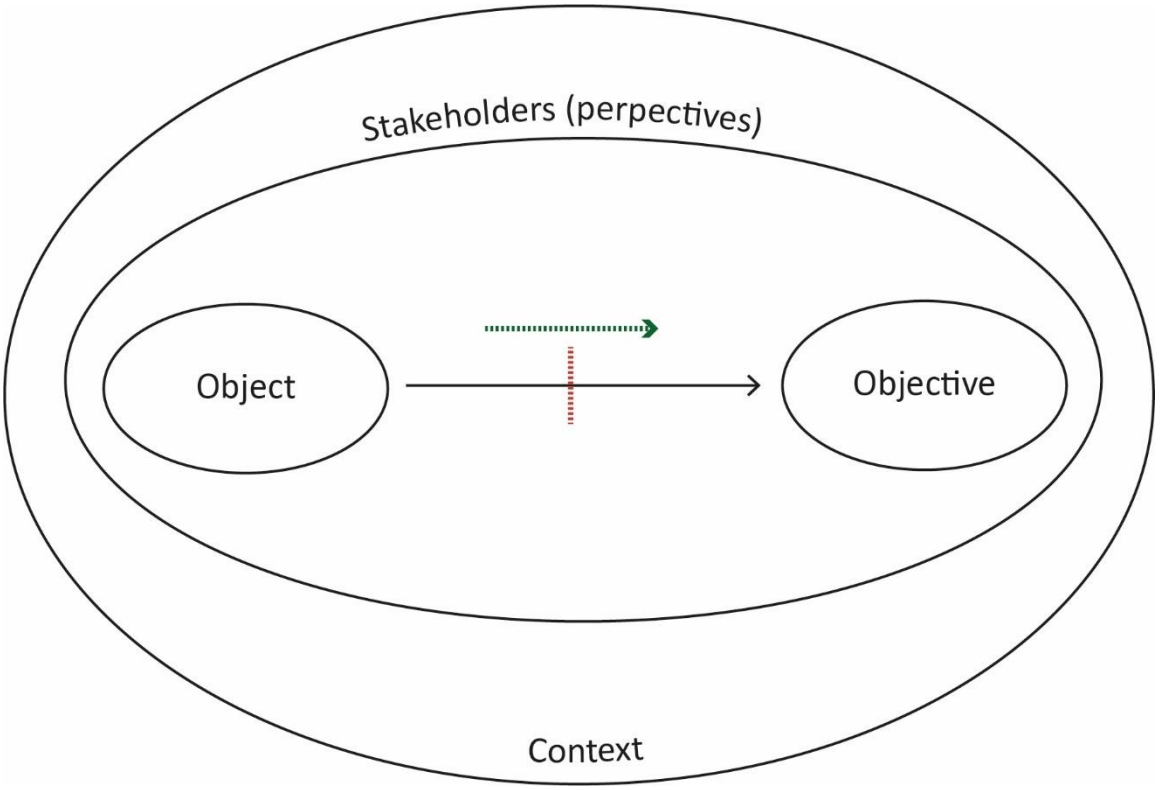


Figure 4.65: Schematic representation of the conceptual framework used as a research approach for this study (improved RA2). This will be adapted considering the method choice. barriers are represented in red while drivers are represented in green. See chapter 2.

From this discussion, it is possible to propose definitions of barriers and drivers that will be considered for the analysis of the case study. Barriers and drivers should therefore be understood as: all the challenges and constraints faced by the stakeholders to achieve a consensus on the technical solution of load-bearing rammed earth façades, given the location of the building and its context. Then, barriers

and drivers will measure what separates the conceptual wall element (during the design) from the final wall element, corresponding to the delivery. Challenges and constraints may be related to technical, economic, political, organisational and socio-cultural factors or a combination of these, and may depend on the context of the building and the normative system. Barriers refer therefore to what prevent consensus-reaching, when drivers refer to what facilitate. Figure 4.66 is a schematic representation of the concept of barriers and drivers in this thesis.

This definition of barriers and drivers, through a consensus-reaching path, will be helpful for the description of this path to which Chapters 5 and 6 will be devoted.

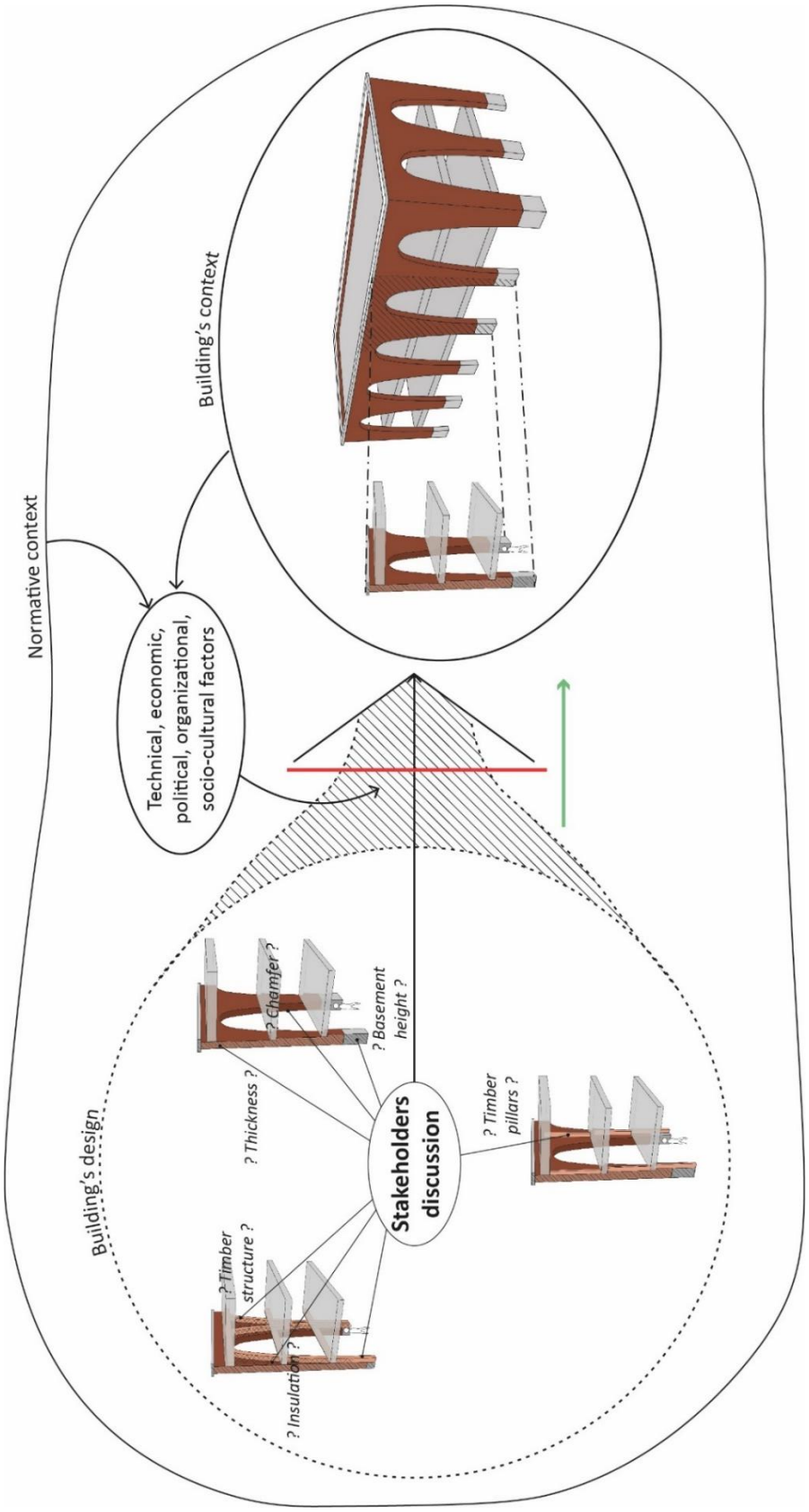


Figure 4.66: Schematic representation of the definition of barriers and drivers in the case study of this thesis

6. Conclusion

Conclusively, this chapter underscored the importance of situating the case study in the French normative system. Particularly, due to the lack of approved standards (defined as a consensus document among professionals assessed by a standards body) for rammed earth construction in France, it became important to underline the interrelationship between the insurance system and standards. Indeed, the higher the degree of standardization achieved, the greater the confidence instilled in insurers. This spotlighted the crucial role played by control officers in this context, especially when their mission is to provide an opinion on the design in comparison with existing standards or regulations. A positive opinion of the control officers is then useful for project owners to obtain their insurance without supplementary costs. However, when approved standards are lacking, control officers sometimes require what is called an “ATEx”, which is a relatively rapid process to obtain a specific standard through approval from a commission of standards experts. More insights will be provided in the next chapter as such a procedure was required by the control officers of the case study. Other elements of context having an influence on barriers and drivers were described. Particularly the moderate size of the case study being part of a larger project offered schedule flexibility, greater financial and technical resources, enabling the absorption of any additional costs both for project owners and designers. Additionally, the targeted labels and the geographical situation in urban areas, offering storage opportunities, were outlined. This will be useful for the understanding of Chapter 5 and 6. The chronology of the building was detailed and reported in a timeline in Appendix D.

Then, the stakeholders involved were underscored and categorised in two groups: (1) the common stakeholders who are involved in the design phase, notably the architects, the structural engineers, thermal and environmental engineers, project owners, control officers and urban planners; (2) uncommon stakeholders, who are not usually involved in the design phase, including earth academics and masons as earth advisors, and the third-party controller who were not used to such mission.

Finally, the object and objective were defined as the conceptual element of wall (object) and the final element of wall (objective), underlining, though, that stakeholders were not necessarily aware of the “objective”. Two main evolutions were highlighted and will be discussed in the next chapter: the load-bearing capacity of the rammed earth and the design of this element of rammed earth walls including different technical choices (specifically, insulation and erosion management).

This helped to propose a definition of barriers and drivers that was necessary for the analysis of the next chapters.

5 A path to a defined wall element: some challenges encountered during the project

Chapter 5 points out different challenges that have been identified in the design process of the building through the description of the evolution of different technical elements, including the questioning of the load-bearing capacity of the wall and the definition of the wall itself. Different technical elements are taken as examples to understand how a consensus was reached (namely the erosion management and the insulation). Finally, insights are provided on the collaborative work and challenges associated.

Parts of this chapter will be published under:
Pelé-Peltier, A., Goizauskas, J., Under review. Toward a situated understanding of challenges in the design and construction of circular raw earth buildings: the case study of a rammed earth office building in France.

1. Introduction

Chapter 4 defined what is considered as barriers and drivers in the case study. Barriers can be considered as all the obstacles toward achieving a consensus while drivers are all the helpful elements. This consensus is the final product of the design and construction process, that is to say, a load-bearing rammed earth wall element without adjuvantation. However, this process followed a path, or a negotiated process between all the stakeholders involved in this project. Therefore, the analysis of this path towards the definition of the wall element is the way chosen in this thesis to analyse the barriers and drivers to the use of load-bearing rammed earth.

In the definition of the element of wall, two different types of dissensus, or consensus reaching, raised from the thematic analysis: one on the load-bearing capacity of the rammed earth wall, which will be investigated in the first section; one on the different technical element chosen for this wall element, that will be described in the second section.

These first two sections will highlight the collaboration of different stakeholders that will be the subject of the last section as being one of the key success factors for the case study.

2. The constant questioning of the load-bearing capacity of rammed earth

The load-bearing capacity of the rammed earth was discussed from the early design phase to the delivery of the building, in different forms. In particular, during the detailed design phase, the technique was questioned by introducing an alternative (poured earth[121]). This will be discussed in the first subsection. Then, the second subsection will describe the questioning of the load-bearing capacity of rammed earth.

2.2. Questioning of rammed earth: rammed earth vs. poured earth

This section addresses the controversy around the choice of the technique highlighting the positioning of the different stakeholders, allowing us to contextualise one of the sources of this controversy, and the arguments for and against. In particular, the latter allows us to notify the arguments against rammed earth that have been developed. Therefore, the subsections will first address the different stakeholders, their roles and the tensions between them to understand better the controversy around the choice of the technique. This will highlight a distinction between two different teams each

[121] Poured earth is a construction technique that is "still in its infancy and [for which] few design options have been reported" (Du et al., 2022). The principle is to use "the tools and methodology applied in modern cement-based concrete building" (Pinel et al., 2017) to pour earth (mixed with adjuvants).

advocating their technique propositions involving different arguments that will be the focus of the second section.

2.2.1. Role and tensions between stakeholders

One of the first tensions between the stakeholders, as described by respondent R01, occurred early in the detailed design phase when the element of the façade was not yet properly defined as described in Chapter 4. This corresponds to the first observable peak on the curve corresponding to the number of exchanged emails according to the timeline of the project (Appendix D).

> *"And so, I remember that there was an initial discussion on this subject where things got rather tense" R01 – Academic*

At that time, there was still talk of having a timber structure to load-bear the façade, while some stakeholders were already supporting load-bearing rammed earth façades. Two competing teams took shape to defend two different technical solutions: one pleading for a timber structure with a poured earth coating; the other defending load-bearing rammed earth façades.

> *"And there was a bit like **two blocks that split up**, us on the side of the architects to defend a solution that made sense [...] and finally the project owners, the control officers and the timber structural engineers who were looking for a more conventional solution" R08 – Structural engineer*

This quote highlights the opposition between the two teams, with the structural engineers seeing themself as the *advocates* of the rammed earth. These two teams will be depicted in the following sections starting with the poured earth team that created doubts among stakeholders of the project. Then, the rammed earth team will be described and presented as advocates of the load-bearing rammed earth proposition. This controversy between the two teams created confusion for the project owner that had their own preoccupations. Finally, the solving of the controversy came with a redefinition of the role of some stakeholders which went with tensions related to conflicting interests.

2.2.1.1. Setting up poured earth team: creating doubts (team PE)

At the beginning of the detailed design phase, different emails and technical documents mentioned the use of poured earth instead of rammed earth for the façades. The potential use of this material

seems to have been confirmed during a meeting involving academics B (as described in Chapter 4). The latter, like the academics A, were called upon for their expertise on earth construction.

At that time, the timber structural engineers, among the discussion on the load-bearing capacity of the earth, expressed their doubts about the possibility to have load-bearing poured earth, using different arguments: highlighting a need for homogeneity between the façade structure and the interior structure for calculation and implementation reasons (connecting different materials). This is how the team defending the timber structure solution for the façade with a poured earth coating was formed, made up of the timber structural engineers and the academics B.

This proposition of poured earth instead of rammed earth raised doubts about the technical feasibility of load-bearing rammed earth, among the stakeholders, as described by one of the academics A:

> *"And so, when they launched this idea, I think that afterwards, it germinated just about everywhere. In other words, everyone thought, "In the end, are we using the earth as it should be used?"* ***And that's when doubts about the technical feasibility of load-bearing rammed earth arches started to appear."*** *R01 – Academic*

This created a conflict of expertise between the two teams constituted.

2.2.1.2. Setting up rammed earth team: defending load-bearing rammed earth (team RE)

Simultaneously with the proposal of non-load bearing poured earth with a load-bearing timber frame proposed by the timber structural engineers, the architects asked the structural engineers to study a proposal for load-bearing rammed earth, thus eliminating the timber structure. In the aftermath, the structural engineers seek the support of academics A to defend a proposal for load-bearing rammed earth façades. It was at this time that the mason became involved in the project, requested by one of the academics A.

Thus, the team defending a proposal for load-bearing rammed earth façades was made up of structural engineers, architects, masons, and academics. This team will then defend a solution of load-bearing rammed earth façades until the end of the construction while we will see later that the load-bearing capacity of the material was constantly questioned until delivery.

2.2.1.3. Preoccupations of the project owners

The technical controversy between poured earth and rammed earth brought confusion to the project owners. In an email[122], during the detailed design phase, addressed to the design team, the project owners indeed recalled the choice of a timber structure for the façade, taken during the competition (although Chapter 4 highlighted that these technical choices were not yet clear to all stakeholders). In this email, they asked the two teams to produce technical documents to justify their proposals.

This email highlights some of the client's concerns regarding the technical choices. Indeed, for each technique used, they asked for validation from the control officer (therefore to a matter of insurability as highlighted in Chapter 4), information on any existing standards on these techniques and finally the cost of each proposal. The economic factor, indeed, already has been reported as a main concern for the clients, particularly in Portugal and Brazil, along with aesthetics and project and construction time factors (Nina et al., 2023).

A first prototyping session of poured earth and rammed earth specimens had been carried out to help the project owners make their choice, as described in Chapter 6.

2.2.1.4. Redefining the role of some stakeholders

As described in Chapter 4, section 3, there was two structural engineers' office on the project: the "timber structural engineers" and what we simply called "structural engineers". It should be noted that at this stage of the project, the structural engineers were involved to design only the earth part of the façade as well as the concrete plan for the project (basements). Besides, the timber structural engineers were involved to design the entire structure, supposedly made of timber.

In the context of this controversy between poured earth and rammed earth, the structural engineers, therefore, proposed a design of the entire building, even though it was not their mission, as one of the structural engineers described it:

> *"And so, at that stage, [...]* ***we took the initiative of making a global proposal for this building****, including the timber frame, the floors and the vertical circulation cores. Designing, drawing, calculating and taking responsibility for them. And so,* ***to do this work that we weren't asked to do or paid for****. But*

[122] Let us remind that, for ethical reasons, it has been decided in this thesis to note make quotations of the emails. Indeed, these sometimes involved many different stakeholders (either structures or individuals) for which it was not possible to obtain agreement to be quoted.

to break the deadlock and take overall responsibility" R08 – Structural engineer

Therefore, the choice of load-bearing rammed earth façades having finally been retained, it was necessary to redefine the missions of the two structural design offices which could have created tensions while these different offices had different interests for the project, including economics.

The role taken by the structural engineers in promoting the load-bearing rammed earth proposal was confirmed by the architect:

"We were lucky to be associated from the beginning with [name of the structural engineer office], who possess the know-how, power and determination to see these projects through to the end." R07 – Architect

More details on the role of various stakeholders will be provided in section 4. Particularly, Section 4.1.3 will describe further the different motivations and interests of the stakeholders identified in the case study.

2.2.2. Arguments developed: raising some challenges for rammed earth

In the context of this controversy, the challenge for the two different teams with their different proposals will be to convince both the project owner and the control officers. Indeed, as already mentioned above, the project owners sought the opinion of the control officers on the two techniques to facilitate their choice. The arguments developed will highlight issues related to the use of rammed earth that were then solved by the design team.

Different types of arguments were put forward by the two teams, relating to environmental, technical, economic, normative, or knowledge and expertise considerations. It should be borne in mind since the data used for the analysis, in particular the emails, were provided by the structural engineers, a bias might exist in the representativeness of the arguments. Indeed, only the email exchange involving or received by the structural engineers was considered. For instance, if they existed, I did not have access to exchanges between Architects and Academics B. Therefore, the description of the argument's pros and cons does not aim for exhaustivity but only to put forward the ones highlighted by some of the stakeholders of the project. Moreover, the chosen methodology can only highlight written arguments, whether in emails or meeting minutes. Therefore, the variety of types of arguments cited below is not

exhaustive. However, analysis of the pros and cons can provide insights into what might be seen as potential barriers and drivers from a stakeholder perspective to the choice of rammed earth.

The arguments in favour of load-bearing rammed earth façades are: the high level of recyclability of the material (if unadjuvanted), put forward by academics B; and the knowledge and skills of the extended design team (i.e. including academics A and the mason).

Different arguments against the load-bearing rammed earth proposal were raised during the detailed design phase, in particular from the team PE. First, academics B raised a potential issue that could represent the erosion of the rammed earth surface. In particular, they noticed that, during the first years following delivery, there will be a deposit of fine earth against the wall, which, according to them, will be badly perceived by end-users. The issue of erosion will be dealt with in section 3.2 to put forward how the design team dealt with this issue. Then, academics B also raised the issue of the potential complexity of the organisation of the construction because the rammed earth is not generally implemented in France between October and March due to the climatic conditions. Chapter 4 has already demonstrated that the inclusion of the case study within a larger project has helped to improve flexibility and alleviate the challenges posed by the seasonal nature of rammed-earth implementation. The on-site prefabrication, which will be described as a key step in Chapter 6, also helped in organizing the construction. The cost argument was also made, arguing that poured earth was inexpensive compared to rammed earth. However, in the cost comparison between the two techniques, the economist of the project highlighted that the poured earth technique was proposed by academic B, while the cost of rammed earth was a contractor's estimation (made by the mason involved at the start of the design phase). More value was assigned to the latter by the economist who considered the contractor's estimation more reliable than the estimation of academics B for poured earth. This has been found in the literature for the case of a cardboard construction prototype project, where the role of the contractor was major in estimating the actual costs, despite the difficulty of such estimates for such projects (Cripps, 2004). Finally, the lack of possible competition due to a lack of manpower, in particular, to implement prefabricated rammed earth, was also highlighted by academics B as an issue for rammed earth. Section 3 will indeed provide some insights into how this lack of competition was perceived as a risk for the project owner. Table 5.16 synthesises the arguments pros and cons raised.

Table 5.16: Table summarizing the pros and cons for rammed earth, identified by the data analysis and raised by the different teams. It should be noted that most of the arguments were raised by Academics B (Team PE).

Arguments	For Rammed Earth	Against Rammed Earth
Team PE	High-level of recyclability	Problem of the perception of erosion by end-users
		Complexity of the organisation of the construction due to climatic conditions
		High-cost
		Lack of competition due to a lack of contractors
Team RE	Knowledge and skills of the extended design team	

The arguments raised against rammed earth can be seen as perceived obstacles by the team PE. Some of these have been underscored as barriers in the literature. For instance, the high cost, although depending on the economic context, is considered by some authors as a barrier (Ben-Alon et al., 2020a; Kulshreshtha et al., 2020; Owino et al., 2014b; Van der Linden et al., 2019b; Zami and Lee, 2011d). In France, Hugo Gasnier also accounted for the high cost as a barrier (Gasnier, 2019, p. 59). Besides, Hugo Gasnier also highlighted the climatic conditions potentially complexifying the organisation of the construction. Indeed, traditionally in this region of France, the period of frost is avoided for the fabrication of rammed earth (Gasnier, 2019, p. 57). Interestingly, all the potential problems notified by the team PE and that can be found in the literature were solved by the stakeholders involved in the case study. Indeed, the building was finally built with load-bearing rammed earth. Therefore, this highlights that barriers both noticed here by some stakeholders and in literature, do not mean obstacles that cannot be overcome at a project's scale.

Finally, from the definition taken for barriers and drivers in this thesis, the conflict between the two teams can be considered a barrier. While both teams were seen as earth experts, this controversy might be explained, at least partially, by a conflict of values.

2.2.3. A conflict of values?

One of the reasons explaining this controversy around the earth technique (rammed earth or poured earth), could be a conflict of values between the stakeholders. Indeed, As already mentioned in this thesis, Villain (2020) defined different groups of stakeholders in earth construction carrying different visions. In particular, he has described a difference between those groups of stakeholders that can be interpreted as follow: (1) some stakeholders advocate a craft-based industry (some of those in order to maintain their social position in the current craft earth construction field in France) and therefore support historical use of earth construction; (2) While others are balanced between historical techniques and industrialisation of earth construction, particularly through developing new techniques similar to those used in mainstream construction. Poured earth is an example of such techniques, using similar tools and methodologies in the concrete industry (Villain, 2020, p. 386). When looking at the introduction of the few articles[123] investigating poured earth, it is indeed possible to identify a logic of productivity and industrialization of earth construction, as highlighted in the following quotation:

> *"In order to be able **to build productively with earth**, and thus replace cement concrete in the construction of small and medium-sized houses, the development of a poured earth construction technique is desirable. Many advantages could be gained from this. **In addition to drastically increasing productivity compared to traditional techniques**, the process would make it possible to conserve the tools and methods of cement concrete technology and, above all, to reduce the labour intensity." (Pinel et al., 2017)*

Therefore, in our case, it seems that these two perspectives are represented in the two teams: team RE advocating the first vision, while team PE the second, which might have to catalyse the dissensus. However, further research would be necessary to better understand how the different visions described by Villain (2020) could interfere when it comes to a specific construction project. This potential conflict of values here has not been thoroughly analysed as it is a complex issue that would require specific research.

2.3. Questioning the load-bearing capacity of rammed earth

As highlighted in Chapter 4 and in the previous section, the load-bearing capacity of the rammed earth walls was not obvious to all the stakeholders and was questioned, in particular by the control officers, from the competition to the delivery. Different alternatives were factored in, including adding timber pillars to support the floors. Two key moments can be cited to understand the dissensus around the

[123] The search "poured earth" on Scopus found 13 documents (the first published in 2012), compared with 1296 documents found for "rammed earth" (the oldest published in 1977).

load-bearing capacity of rammed earth: (1) the ATEx procedure and its refusal and (2) the delivery time.

2.3.1. Unfavourable ATEx

As explained in Chapter 4, in the case of a construction technique that does not have an *approved*[124] standard, such as rammed earth, control officers can require an ATEx procedure[125]. As will be seen in this section, the latter was not desired by the project owner. The design team argued for avoiding such a procedure, emphasizing: (1) the traditional character of rammed earth, (2) the skills of the design team and the masons, and (3) the performance approach (that will be described in Chapter 6) to justify the design. However, the control officers finally required an ATEx procedure due, in particular, to the specific arched architecture of the project, considered to be a non-traditional use of the rammed earth technique. The ATEx was rejected by the French standards organisation. The reasons for this refusal will be developed in this section, as well as the reasons why some stakeholders wanted to avoid it and how the project continued despite this rejection.

2.3.1.1. An unwanted procedure… which delayed its launch?

The ATEx procedure was particularly unwanted by the project owner. Indeed, it represents various constraints. Firstly, it is seen as a risk (in the event of refusal) and a cost, according to the structural engineer interviewed:

> *"The project owners didn't want an ATEx, because they knew that it was a risk, that it cost money, that there was a risk of being rejected..." R08 – structural engineer*

Besides the cost, the ATEx procedure also represents a time constraint on the project. The time constraints come both from the administrative schedule of the procedure and from the production of the report for which different technical justifications must be developed to answer the questions raised by the standards organisation. Usually, to establish these justifications, it is possible to rely on standards (for example, if the innovation is the assembly of different already standardized processes, candidates for innovation can rely on the standard relating to these processes). However, in the case of rammed earth constructions, due to the lack of standards, the ATEx report is more difficult to establish, which requires more investment:

[124] By the French organism responsible to validate standards
[125] See chapter 4 for a definition of this procedure

> *"In the case of raw earth, the problem is that you have systematically to invest a lot to put together the technical file because the level of knowledge[126] about this process is low." R05 – Standards organisation employee*

These are the reasons why stakeholders may be reluctant to use such procedures. This may also be a reason why the control officers were slow to demand the procedure in the case study. The latter started when the manufacture of the first blocks began and the contract was signed with the masons.

> *"In the end, they requested an ATEx. Except that the contracts had already been signed with the company, and we'd already started making blocks that would be put out to dry over the winter. We had started all this before we even knew, I think officially, that an ATEx had been requested." R08 – Structural engineer*

2.3.1.2. A procedure carried out by the masons and the structural engineers

In the project, the stakeholders considered innovators were the masons who had to carry, in the name of their structure, the establishment of the ATEx report. However, such a complicated procedure would probably not have been possible without the help of structural engineers, as highlighted by the academic interviewed:

> *"[name of the structural design office] created the ATEx report for the construction company. In other words, [name of the masons' company] was unable to submit an ATEx" R01 – Academic*

Although it was not specified by the interviewees, we can assume that this inability is due to the small size of the construction company (that will be discussed later in section 4), and not having the capacity to assume the technical engineering skills required by such a procedure.

The structural engineers played an important role here while the quality of the report was recognized by the control officer:

[126] Here knowledge should be understood as knowledge for standardization (i.e. engineering and scientific knowledge).

> *"The report that was presented was really very, very strong. Truly very strong" R04 – Control officer*

However, it was ultimately refused by the commission[127] responsible for evaluating it.

2.3.1.3. A rejected ATEx which was finally not necessary as the project continued

Various reasons may explain this refusal by the ATEx commission including the difficulty of justifying certain technical elements, as raised by the control officer interviewed:

> *"It gave an unfavourable opinion, quite simply **because in the logic of the qualification, we were unable to justify a certain number of things** [...] and these things continued to be at the centre of the debate" R04 – Control officer*

This lack of "justification" could be understood as a lack of engineered (calculation, models, …) justification to which the commission is accustomed. Indeed, the ATEx report contained both engineered justifications and justifications based on experience. For instance, as there was a lack of scientific knowledge on the fire resistance of rammed earth and laboratory testing would have been too costly, the fire resistance of the rammed earth was mainly[128] justified in the ATEx report by referring to the fires that occurred in Australia in February 2009. Indeed, the expert reports highlighted that only rammed earth stands after the fires. However, this justification was considered insufficient by the commission. This issue of the different expected forms of justification already has been observed by Henderson (2007) in the case of establishing new standards for straw bales in the US. Indeed, the author investigated, through observation, in-depth interviews and discourse analysis, how straw bale advocates tried to convince code officials of the viability of their techniques. Twenty experimental permits were granted in New Mexico to experiment and gather information on straw bale construction. But there were different expectations on the type of information collected between straw bale advocates and code officials, as highlighted in this quote:

> *"And perhaps herein lies the roots of the subsequent misunderstandings between straw bale advocates and code officials when they began to collaborate on writing a standard together. The code officials and the straw bale advocates had very different*

[127] This commission already is introduced in Chapter 4.
[128] References to Australian fire resistance reports and swiss rules were also noted in the ATEx report to justify fire resistance of rammed earth.

> *expectations of the experiment permits.* ***The building code officials expected consistent measurement, testing, and numbers****.* ***The straw bale advocates gave them*** *the kind of information that was conveyed in workshops –* ***how to build incrementally a building, with photographic documentation****." (Henderson, 2007, p. 15)*

In the case study, after the rejection of the ATEx by the commission. The control officers agreed to make an exception by accepting the fire resistance proposed by the structural engineers and pointed out that it could not be generalized to other rammed earth projects.

Among the technical issues that remained in the debate after the rejection of the ATEx, are the partial safety factor, and the creep[129] of the rammed earth wall.

The partial safety factor is the factor applied to the compressive strength (or more generally any mechanical properties of the material accounted for the design) of the material allowing the wall to be oversized in order to factor in unforeseen constraints or disorders. This factor, therefore, aims to minimize the compressive strength. Besides, similar factors are used to maximize the applied loads to account for any exceptional building use. More details will be provided on what is the safety factor in Chapter 6.

"The main reason for rejecting ATEx was an unreasonable safety factor." R08 – Structural engineer

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For the project, the structural engineers proposed a safety factor, considered too low by the ATEx commission. Indeed, the aim for the structural engineers was to optimize the thickness of the structure by choosing the smallest safety factor, which had not been identified as problematic by the other stakeholders until the ATEx commission (including control officers). They justified the use of a low safety factor by the skills of the masons, the characterization and the quality control procedures to put in place for the project and which will be described in Chapter 6.

Other reasons for the refusal of the ATEx were raised during the interviews but would require further investigation to be confirmed or detailed as they were only raised by one interviewee and were difficult to discern through the analysis of the emails. Among these, we could highlight a potential conflict of interest between the commission and some of the stakeholders involved in the project; a lack of

[129] Creep is the tendency of a solid material to undergo slow deformation while subject to persistent mechanical stresses (source: https://en.wikipedia.org/wiki/Creep_(deformation)). The consideration of time is major for this phenomenon as any solid material creep under gravity for example, but the timescale can be very wide.

knowledge about earth construction among the commission participants; and a lack of trust in the expertise of the different stakeholders of the project.

Finally, despite the refusal of the ATEx, the project continued and the control officers decided to provide their advice without the need for the ATEx. To do so, control officers had to scale up in the hierarchy by involving senior control officers having greater responsibilities in the project (see section 4.2). Different reasons could explain this decision. Among those, the fact that the construction has started was pointed out by the structural engineers. Indeed, while, in the one hand, this represented a difficulty in responding to the issues raised by the commission, because the design could no longer evolve:

> *"The difficulty was that we had no room to manoeuvre. We could no longer change the design" R08 – Structural engineer*

In the other hand, it was arguably difficult to back out of the rammed earth wall for the control officers and the project owner, because (1) publicity already have been made on the use of rammed earth and (2) the construction had already begun, as highlighted by the structural engineer:

> *"What enabled us to get the project off the ground was the fact that we had started working on it" R08 – Structural engineer*

However, this decision was accompanied by requirements, on the part of the control officers, of different justifications and quality control which are developed in Chapter 6.

Finally, since the refusal of the ATEx, a controversy has reappeared, mainly between the structural engineers and the control officers, on the load-bearing rammed earth capacity of the walls. Control officers demanded the addition of pillars while structural engineers still advocated fully load-bearing rammed earth. Different technical solutions were taken into consideration during this period and depending on the problem addressed: initially, the control officers proposed to add pillars on the two first levels of the building, where the load was the greatest, to increase the safety coefficient. This proposal was abandoned but the reasons could not be found in the data. This abandonment probably was the result of a negotiation between control officers and structural engineers. Finally, there remained the issue of creep, to which the control officers proposed adding precautionary posts with

the idea that the floors would rest on the pillars in the event of excessive deformations. However, the design team was against this proposal and the debate was held until the delivery of the building.

2.3.2. The delivery: a matter of insurance

At the delivery stage, the controversy over whether or not to add pillars had still not been resolved. In this context, a power struggle concentrated between the advocates of load-bearing rammed earth (masons, architects, structural engineers) and the other stakeholders (The control officers on the one hand and the project owners on the other). This issue revolved around insurance matters. Indeed, the project owners needed both all the insurance of the design team stakeholders and a positive opinion from the control officers, in order to obtain their insurance. However, different stakeholders from the design team refused to provide their insurance in the event of non-load-bearing rammed earth. This was argued by considering that the addition of pillars would ultimately be dangerous for the structure. More specifically for the masons, the latter argued that they have signed a load-bearing rammed earth contract, which was covered by their insurance, but their insurance did not cover non-load-bearing rammed earth by adding pillars.

In the end, a consensus was adopted: the pillars were manufactured but not installed, and they were supposed to be installed only if the rammed earth flowed. In that context, the control officers agreed to give a positive opinion on the condition of monitoring the creep (which will be described later in Chapter 6).

2.4. Conclusion of the section

The first subsection highlights that one of the first barriers (i.e. creating dissensus among stakeholders) to the choice of load-bearing rammed earth was a conflict between two teams of stakeholders, which left the project owners confused. Indeed, the introduction of the idea of replacing rammed earth with poured earth by Academics B created doubts. This highlights the importance of having all stakeholders convinced of the technique (in our case, rammed earth) as early as possible in the design to prevent such conflict. Then, either reducing the number of stakeholders involved (here a redundancy with the academics and the two structural design offices) or being mindful of the potential differences in values among stakeholders (along with the varied interests) could be ways to enhance project management and avert such situations. However, this conflict had the advantage to raise various issues about the use of rammed earth, which will be discussed in the upcoming sections and Chapter 6. These issues include erosion management (see section 3.2.), a lack of competition due to a scarcity of contractors (see section 4.3.), or the complexity of the construction organization due to climatic conditions (see Chapter 6).

The second subsection showed how the load-bearing capacity of rammed earth was consistently questioned, highlighting at least a lack of confidence in load-bearing rammed earth and/or in the design proposed, in particular from the control officers. This might be explained by a lack of approved standards and engineered scientific data that could help to justify the load-bearing capacity of the rammed earth walls. This section serves as an example of the barriers encountered by design teams when designing with unstandardized (meaning no approved standard) materials. It also underscores the central role played by control officers, as previously described in Chapter 4 within the context of the French standard and insurance system.

The two significant moments that illustrate the questioning of the load-bearing capacity occurred during the ATEx and the delivery phases (corresponding to two peaks of email communication in Appendix D). This underscores the importance of insurance in these decision processes. Indeed, as highlighted in Chapter 4, the ATEx procedure is interdependent on the favourable opinion of control officers and therefore facilitates insurance obtention without supplementary costs. Additionally, at the delivery, the insurance of some stakeholders was used by them as a means for negotiations. The section also highlights the crucial role played by the structural engineers in the case study who advocated for the adoption of load-bearing rammed earth.

While the load-bearing capacity was a major point of discussion during the design, other aspects of the wall's design were also subject to debate as the next section will demonstrate.

3. Toward a simple element of wall: reaching consensus

3.2. Water sensitivity: a notion that afraid stakeholders?

The issue of earth material sensitivity to water is often cited in the literature as representing a barrier (Bosman, 2015; El-Sawalhi and Ajwa, 2013; Hadjri et al., 2007), closely linked to the durability of the material, also described as a major concern (Danso, 2013; Kulshreshtha et al., 2020; Owino et al., 2014b). Moreover, studies investigating the adjuvantation of the material sometimes introduce their articles by insisting on the "high vulnerability to water erosion" which would act as a barrier (Cuccurullo et al., 2022).

As part of the case study, various stakeholders highlighted the water sensitivity of the earth material as being uncommon in the field of construction which would create distrust among professionals toward the material:

> *"**The world of construction has been moulded and shaped by the irreversibility of the hydraulic reaction** [of concrete, or cement mortars]. **And we've come to offer them something that is totally reversible and therefore something that needs to be maintained, monitored, protected and built in certain conditions**... It's not something that comes naturally, and so it's something that **creates a degree of mistrust**." R04 – Control officer*

This respondent insists on the reversibility of the interaction between earth, in particular clays, and the water. It should be noted that this reversibility is also an advantage of the earth material, particularly from an environmental perspective when it facilitates its recyclability and provides its well-known hygro-thermal properties (Morel et al., 2021b). This notion of fear caused by water sensitivity, and perhaps the lack of knowledge about managing this sensitivity, was also put forward by the academic:

> *"A material that's sensitive to water like that, that can potentially collapse due to humidity, that's scary." R01 – Academic*

The question of the material's sensitivity to water is therefore important to deal with and can be split into two issues: erosion and structural stability over time. Regarding the case study, the management of the former will be discussed here. The question of stability over time of the rammed earth will be discussed thoroughly in Chapter 6, while this section will address the insulation topic (in our case, its absence) as it also raised concerns about the rammed earth stability over time.

3.3. The example of erosion: a simple path to consensus

The erosion was managed by the extended design team without important dissensus. This section will therefore describe the story of erosion management first to then propose a representation based on Ishikawa diagrams that helped to make visible the different problems raised and solutions adopted accordingly.

3.3.1. A story of the erosion management

The issue of erosion[130] was raised early in the design of the building. Indeed, competition documents mentioned it and in exchanges of emails between academics[131] and structural engineers, the latter mentioned the issue of erosion as a potential apprehension for the project owners. Besides, describing the issue of erosion will illustrate the interest in the approach inspired by Science and Technology Studies (STS) (Described in Chapter 3). In particular, the technical, organisational but also socio-cultural causes of this issue will be highlighted.

Two potential problems linked to erosion have been identified: the loss of material on the surface which would lead to a change in the appearance of the surface; a potential deposit of earth at the foot of the wall; and the potential brittleness of the corners of the building.

3.3.1.1. Causes of the problem of erosion

Different causes of the erosion problem have been identified which can be categorized using the same categories as in Chapter 2, in particular the technical, socio-cultural, and organisational causes.

First of all, technical causes should be thought about in the context of the building. Indeed, erosion is closely linked to water sensitivity and therefore climatic conditions (see for example (Q. B. Bui et al., 2009) for an assessment of the durability of rammed earth exposed to weather over 20 years) and exposure of the building to rain. This highlights the contextualisation needed to address the issue of erosion. This was actually factored in by the architects:

> *"We are also in a context where the building is not necessarily exposed in the same way as in the countryside. [...] Here the urban context is with high buildings all around that act as a screen" R07 - Architect*

Regarding the risk of failure of the edges of the building, the organisational cause interferes because the design team pointed out the risk of impact with construction machinery that could lead to the failure of these brittle angles.

Finally, socio-cultural causes include the perception of the project owners, as already noted before, and the hypothetical misperception of end users. The STS teaches us that designers, when designing a technical object (here the architectural project), make assumptions about how this object will fit into

[130] In the case of rammed earth erosion can be understood as gradual material loss from the wall surface due to climatic conditions (wind, rain,…) (Q. B. Bui et al., 2009)

[131] It should be reminded, as defined in Chapter 4, that Academics refer now to Academics A, as the Academics B were involved in the project only during the detailed design phase while the Academics A were involved until the building's delivery.

its environment. Here, the environment is to be understood in a broad sense, including the social environment. Indeed, they notably construct hypotheses on the interactions between users and the object in question. This corresponds to the sending phenomena described in the STS (Akrich et al., 2006, p. 163). In the case study, different assumptions were made about the behaviour of end-users toward the earth material. On the one hand, assumed by academics B, the deposit of earth at the base of the wall due to erosion would be badly perceived by end-users, particularly in urban areas. This has been indeed underscored in the literature in the US by Ben-Alon et al. (2020). Indeed, the authors interviewed earth construction experts[132] that reported that clients often consider earth construction as “dirty”. However, it should be noticed that this result is based only on the opinions of experts which could be biased in the assumption of what people perceive of earth. To complete this study Ben-alon (2020) in her PhD thesis, investigated the perception of earth construction through a survey addressed worldwide. Nevertheless, no existing study[133] in the French context can confirm the hypothesis of academics B in the perception of the deposit of earth in case of erosion. On the other hand, the structural engineers considered that end-users discovering the building would be questioned and would tend to touch the rammed earth wall causing potential degradation (see Figure 5.67).

[132] 10 experts composed of two civil engineers, four architects, one regulatory expert and three builders.
[133] Such study, investigating the perceptions of earth buildings, exist in South Africa (Bosman, 2015)



Figure 5.67: Picture of students discovering the rammed earth, touching the wall. This illustrates the assumption made by the structural engineers, but of course, is not enough to validate the hypothesis. The picture has been taken by the author during a class visit to the building in 2022. (source: author)

Hence, this section highlights the complexity and variety of problems and causes (technical, socio-cultural or organisational), at least those perceived by the designers and taken into consideration to deal with the issue of erosion. This description of the various erosion-related problems is important for understanding the technical choices made by the stakeholders to overcome this problem, which will now be described.

3.3.1.2. Technical choices to overcome the problem of erosion

To overcome the issue of erosion, different solutions have been proposed and some have been retained. For instance, in the competition files, it appeared that the structural engineers were proposing to use lime as an adjuvant to counteract erosion. However, the idea was quickly abandoned for various reasons. The masons were reluctant to the adjuvantation, emphasizing the risk that lime adjuvantation could represent in the event of frost[134]. Furthermore, most stakeholders agreed that the

[134] One should be aware that this section aims at describing the arguments put forward by the different stakeholders that influenced the decisions. The purpose is not to assess the validity of the arguments. In

main purpose of using lime adjuvantation is to reassure others, thus raising educational and cultural issues. This confirms what has been pointed out in the literature where adjuvantation is used to reassure clients or insurance offices, particularly regarding the perceived low durability of the material (Ben-Alon et al., 2020a; Marsh et al., 2020). Therefore, the decision not to adjuvant the material was made early in the design phases.

Most of the technical decisions were taken in collaboration with the mason whose important role in the design was, once again, underlined by various stakeholders, including the structural engineer:

> *"Here too, **thanks to the masons' reflexes, common senses, and feedback from analysing the heritage, we learned a lot during the project.** Without the masons, such things would have taken us a long time to achieve and we wouldn't have done properly the construction details that would have led to ageing or deteriorating of the material. This doesn't mean that the building would have collapsed, though. So, **we anticipated certain things that I think are very smart for the project**." R08 – Structural engineer*

Similarly, the architects reported that the use of chamfers to reduce the risk of breaking the edges of the building was decided and designed in collaboration with the mason:

> *"Bevels were made on the corners and inside the vaults to avoid sharp edges and reduce the risks of breakage. **The decision has been made with the masons.** We even made it an architectural subject, with this bevel which is degressive and which also plays with the shape of the vault." R07 – Architect*

The consideration, given to the mason, by the structural engineer and the architect interviewed showcases the importance of practical knowledge in the technical choices made during the design. This tends to confirm recommendations made in the literature to involve the masons early in the design of earth buildings (Morel et al., 2021b).

particular, the argument of the risk that lime adjuvantation could represent in the event of frost lays on the knowledge of the mason, but is not necessary valid.

Other technical choices include brushing off the rammed earth and applying glue to reduce the risk of loss of surface material. Indeed, brushing, as described by the structural engineer, allowed to remove the fine part that would have constituted the potential deposit:

> *"To anticipate erosion, the rammed earth was brushed while it was still fresh [i.e. just after manufacturing] to achieve a pre-erosion so that the final appearance is obtained straight away and does not have any differentiated ageing between the façades, or any deposit of earth at the foot of the wall."*
> *R08 – Structural engineer*

The glue was applied on the entire face of the rammed earth wall in order to avoid loss of material on the inside or, for instance, deposit on the clothes of the end users. This was again a solution proposed by the masons.

Finally, the height of the base has been increased, compared to what was planned during the competition, to the height of human size (about 1m60) for various reasons: to discourage end-users from coming to scratching the wall (Figure 5.67) and to reduce the risk of shock with construction machinery. All these decisions were taken during the detailed design phase.

This section underscores the various technical choices made in collaboration between stakeholders of the extended design team. The erosion management seems not to have represented major difficulties in the design. These choices and solutions can be represented regarding the issues they address through an adapted Ishikawa diagram which is the purpose of the following section.

3.3.2. A representation of the issue of erosion: adapted Ishikawa diagram

The Ishikawa diagram is a frequently used qualitative tool in the field of quality management, to schematically represent the interrelationships between causes and results (problems) (Leśniak et al., 2021). This tool already has been used in the construction sector for different purposes: to study barriers to the implementation of BIM in construction (Leśniak et al., 2021) or to diagnose failures of construction projects (Al-Zwainy et al., 2018). The causes are separated into the category of causes that are generally five in number: Manpower, Methods, Machinery, Material, and Management, to which it is possible to add Environment and Money. In the case study, it has been decided to follow the previous categories which are: technical, political, economic, organizational and socio-cultural. Moreover, in addition to the representation of the causes and sub-causes, it was decided to represent

the solutions taken into consideration and adopted. Figure 5.68 represents the Ishikawa diagram adapted for the issue of erosion.

It is worth noting that a cause can also be considered as a problem and a solution can also raise new problems.

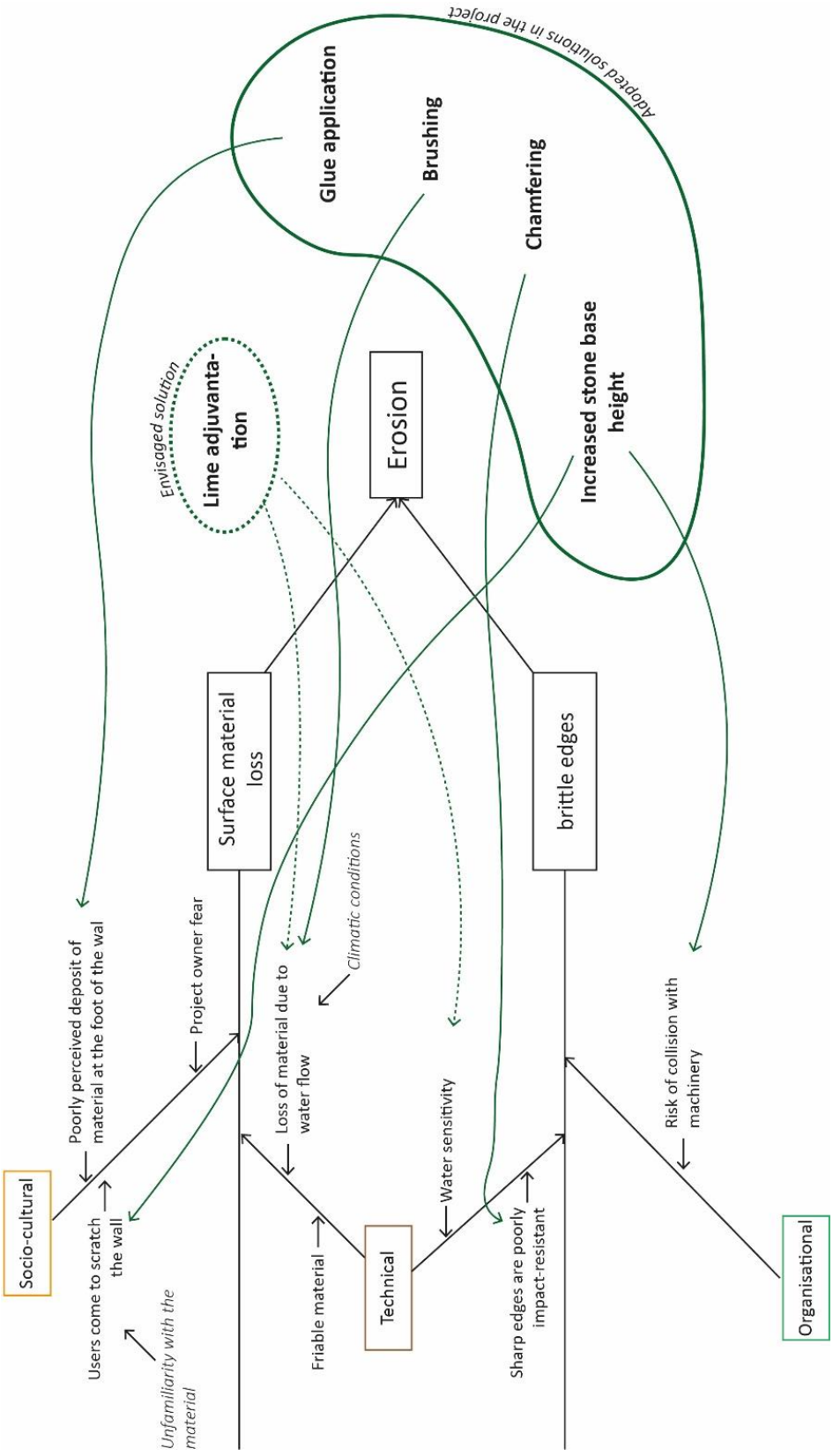

Figure 5.68: Adapted Ishikawa diagram summarizing the issue of erosion of the material and how the stakeholders managed it

This section underlines the fact that a proper design can address the different issues related to the erosion of the rammed earth wall, as it is sometimes recognized in the literature (Beckett et al., 2020)

3.4. The example of insulation: a controversial issue involving various stakeholders

Compared with erosion management, the insulation was much more controversial in the project. This section will first describe the controversy around the insulation and then underscore the great variety of stakeholders involved in the decision.

3.4.1. A controversial issue that stands until the construction phase

At the time of the competition, insulation for the earthen wall was planned. This was notably required to follow the thermal and environmental labels described in Chapter 4. However, the data shows that during the early design phase, one of the academics A suggested that insulation was not necessary. This was a starting point of a long polemical debate between the stakeholders until the decision to abandon the insulation, that was made during the construction phase.

Various reasons, including technical issues as well as normative or aesthetic considerations, have contributed to the decision to abandon insulation despite the high requirements associated with the targeted labels. First of all, at the beginning of the detailed design phase, one of the masons highlighted the risk of water accumulation in the wall linked to the sensitivity to the water of the rammed earth's compressive strength, this on what the academics agreed, as the structural engineer and the architect pointed out:

> *"We spoke with **the academics and the masons**, and **they alerted us to the material's sensitivity to water** and the risks that could be posed by unsuitable wall layers." R08 – Structural engineer*

> *"It was [Name of the mason] in particular who warned us about the problem of dew point[135] and possible dampness inside, which could be harmful to the rammed earth". R07 – Architect*

The latter quotation underscores once again the important role played by the practical knowledge of the masons in the design of the building.

[135] Condensation

Quite early in the project, masons, academics, structural engineers and architects therefore came up with the idea of not insulating the rammed earth. Moreover, it corresponded to the architects' desire to have visible rammed earth walls on both sides of the building (inside and outside) for aesthetics reasons. Indeed, the aesthetic of rammed earth, related to the material's textural, chromatic characteristics and mass, already have been reported as a driver (Strazzeri and Karrech, 2023). In addition, there was also a risk of slowing down the drying process of the walls in the case of insulating. The thermal engineers were initially reluctant to this idea but were finally convinced when they further calculated and realised that the absence of insulation would benefit summer comfort:

> *"So that's when the idea came up not to insulate the rammed earth, we realised that in terms of summer comfort, there was a real gap between insulated rammed earth and uninsulated rammed earth, the latter being very beneficial for summer comfort. We don't see this so often, at least not to such an extent. So, we took a look at what it was like in winter. And in winter we noticed a sharp increase in our heating requirements. But* ***in the end, the gains with passive cooling for this building were higher than the losses for heating in winter****, even if you think about it from an energy point of view****. So, it made sense not to insulate.*** *We spent more energy on heating, but the proportion of heating costs was lower than the gain on cooling" Respondent 06 – Thermal engineer*

This underlines how the thermal engineers changed their position about the insulation of rammed earth, thanks to exchanging knowledge with other stakeholders (masons, academics, and structural engineers). This could be discussed in regards to the inadequacy of some thermal regulations, requesting in our case for the thermal engineer to go further those. Indeed, authors have already pointed out that thermal regulations are sometimes not suited to the thermal performance of the earth. The current disregard for the inertia of the materials leads to an underestimation of their properties. Thus, thermal comfort conditions can actually be achieved without meeting the thermal insulation requirements (Fernandes et al., 2019). Similar issues have been reported recently in Australia (Strazzeri and Karrech, 2023).

In the end, the decision was made during the ATEx procedure, at the start of the construction phase. Indeed, the use of insulation complicated the justification of the design to the standard organisation.

It would have raised specific issues, including water sensitivity, requiring additional justification from the design team that would have been difficult to achieve, as the thermal engineer explained:

> *"**As part of the ATEx, we were asked to justify that there would be no condensation in the material, and we couldn't provide this proof**. As soon as it was insulated, there was a risk of condensation. Of course, the material breathes and dries, but we couldn't provide the proof we were looking for. And the only way to avoid this was to use a traditional rammed earth technique [i.e. without insulation in our case]. So, **this was also a facilitating factor in the ATEx application, because otherwise it would have been blocked**" R06 – Thermal engineer*

Therefore, facilitating the ATEx procedure was the last reason to convince all stakeholders to abandon the idea of insulating the walls.

Finally, it should be noted that this issue is dependent on the context and in particular on the program of the building. Indeed, the project owner and the thermal engineer interviewed indicated that having an office program was easier to manage than it would have been for a housing program with higher thermal requirements. Thus, if the building had been intended for a housing program, it would have been harder to justify in terms of thermal performance the absence of insulation, and therefore the ATEx procedure would have been even more complicated:

> *"If this programme had included housing, I think the balance between the need for heat and the need for cold would have been different, and a thermal correction would probably have been necessary. And we certainly wouldn't have been able to justify it to the [name of the standard organisation providing ATEx]." R06 – Thermal engineer*

This section underscores the various reasons for abandoning the insulation which are technical, but also due to the ATEx procedure (political). It also raises the issue of convincing all stakeholders through these various arguments. The exchange of knowledge between stakeholders allowed in particular the thermal engineers to change in position.

3.4.2. A negotiated process implying various stakeholders

Similarly, to other technical issues, such as erosion, the choice of uninsulated rammed earth is the result of a long, negotiated process involving various constraints and arguments and various stakeholders. Indeed, as underlined in the previous section most of the stakeholders have been involved in the debate. This went so far as to negotiate a derogation with the urban planners not to follow the requirements of the labels. The urban planners accepted the proposal made by the project's stakeholders (this proposition was carried to the urban planners by the thermal engineer and project owner) on the condition of having instrumented monitoring of the building's comfort and energy consumption for two years after delivery[136]. A PhD thesis is in progress, entitled "*Theoretical and experimental modelling of the hygrothermal and energetic behaviour of raw earth construction: from a complex model to an application model" (Theo Boupard, started in 2022)*. The PhD candidate uses data collected from the building to establish a thermal model to help thermal engineers in the design of rammed earth buildings.

Moreover, it seems that, due to the water sensitivity of the material, a close collaboration between structural engineers and thermal engineers is particularly necessary, as the structural engineer pointed out:

> *"So, **these are aspects of hygrothermics that have a structural impact**. On the other hand, to carry out this hygrothermal study, we also need to understand the conditions of interior use, so we need to know whether the building will be heated or ventilated. [...] What will it be used for? [...] And **all that must be assessed by a thermal design office, implying working systematically with such a design office to come up with a global solution**. The other strategy to come up with a global solution is to become a thermal design office along with structural engineers" R8 – Structural engineer*

3.5. Conclusion of the section

This section addressed issues related to water's sensitivity of the earth material, erosion management and insulation. While water sensitivity has been often highlighted as a barrier in the literature, this section highlights that a proper design can easily overcome most of the problems related. The two examples show the various reasons for the design choices made by the stakeholders to attain the final

[136] See chapter 6 for the description of the different monitoring applied to the building

element of the wall. Those reasons are not only technical but had socio-cultural or political implications (particularly normative). In both examples, the final choices resulted from a negotiated and collaborative process (more or less easy, more or less long) between stakeholders. The latter have evolved in their understanding of the material and its properties, which was facilitated by knowledge exchange among the different stakeholders. Particularly the practical knowledge of the masons was valuable. This collaborative work appeared therefore as a key for the success of the project, which will be the purpose of the next section to describe further.

4. A collaborative work

According to Gasnier (2019), the years of specialisation of the various construction trades have led to a temporal and structural separation of the work of each stakeholder in the design and construction process. However, using earth in construction would require breaking out this separation system and would require collaborative work within the project team (Gasnier, 2019, p. 239). This need of collaboration is already depicted in various literature: Kershaw and Simm (2014) highlighted, through the study of the answers of a panel of experts using the Delphi method, that "*greater communication within the design team and between the design team and the client and end-users could overcome the majority of the barriers facing the implementation of low carbon school design*" (Kershaw and Simm, 2014); by studying the barriers to the implementation of sustainable structural materials in green buildings, Griffin et al. (2010) highlighted the importance of having all stakeholders working collaboratively to achieve the goal of green building; or, for the case of the use of timber in multi-story and non-residential construction projects, Gosselin et al. (2016) believe that most of the problems, observed in meeting minutes, during on-site construction could be avoided by collaborative work of all stakeholders (developers, architects, engineers, builders and suppliers) having worked collaboratively during the design phase.

Collaborative work appears as a key in the literature (concerning earth construction but also more generally sustainable construction or other constructions with low-carbon materials). However, the conditions of this collaboration in earth construction field have not yet been investigated. This section will therefore focus on describing these conditions. This will make it possible for us to understand the motivations, but also the challenges encountered in this collaboration.

4.2. Working as a team: a condition of success

Collaboration work between the various stakeholders and particularly within the extended design team is probably one of the main conditions of success described by the various interviewees,

confirming what was found in the literature. Indeed, when asked about the condition of the success of the project some interviewees replied:

> *"I'd say **it's the will of everyone to move in the same direction**. If everyone hadn't wanted to move in the same direction, we wouldn't have succeeded. [...] You really need everyone, all the partners in the team, to want to move in the same direction and make it to the end." R03 – Project owner*

> *"**The main condition for success is an encounter between people**. That's what it's all about, actually. It happened because people wanted it to happen." R01 – Academic*

This collaboration can be represented through the technical decisions taken to reach the final element of the wall, and sometimes involving a wide variety of stakeholders. Some conditions of this collaboration between stakeholders include their qualifications and skills, and the different motivations of the various stakeholders, but still gathered around the common motivation to build a showcase building.

4.2.1. A representation of collaboration in the technical decisions

The analysis of the documents and emails made it possible to trace the evolution of the technical choices during the project with the various stakeholders involved in these choices. In particular, it was sometimes possible to identify which stakeholders raised the different proposals for the evolution of the facade element and to identify between which stakeholders a discussion took place on these different aspects. However, this identification was not always possible or some information may have been missing. For instance, it is possible that certain ideas or decisions were taken in a meeting without being reported in the meeting minutes, or by telephone for which no data could be collected. Therefore, the information provided in this section is not exhaustive. Exhaustiveness was not sought, it was a question of obtaining a representation of the collaboration to illustrate the variety of stakeholders involved in technical choices.

So, various technical choices can be accounted for, including the various thickness of the wall, the layout of the prefabricated blocks, the connection between the timber beams and the rammed earth, the absence of insulation or the management of erosion (brushing and chamfers), and finally the justification of the compressive strength.

Most of those technical choices were taken in agreement with the masons during the detailed design phase. For instance, the use of steel plates for the connections between rammed earth and timber beams was first proposed by the masons and then discussed/optimised with the structural engineers. The final solution was therefore the result of many discussions between the mason and the structural engineer relative to the implementation and the design of the steel plates. Besides, the masons intervened in the decisions concerning the arrangement of blocks or the thickness of the walls:

> *"We validated several solutions with the mason. In particular, the thickness of the walls, the layout of the elements... We also worked with the structural engineer on how the floors were to be connected to the façade." Respondent R07 – Architects*

In addition, some of these technical choices were also discussed with academics. Indeed, the data revealed that it was primarily one of the academics who proposed a walled fruit by level (i.e. with a wall thickness decreasing from 80cm by 65cm to 50cm according to the storey). Chamfers and brushing are also solutions proposed by the same academic and were later discussed between the masons and the design team.

Figure 5.69 represents the identified involvement of stakeholders in the technical choices. This figure underlines the involvement of the masons in multiple technical decisions, during the design phase, highlighting, once again, their important role which will be described in further sections. Once again, this figure is not exhaustive but identifies the main stakeholders involved in the discussion about these different technical elements.

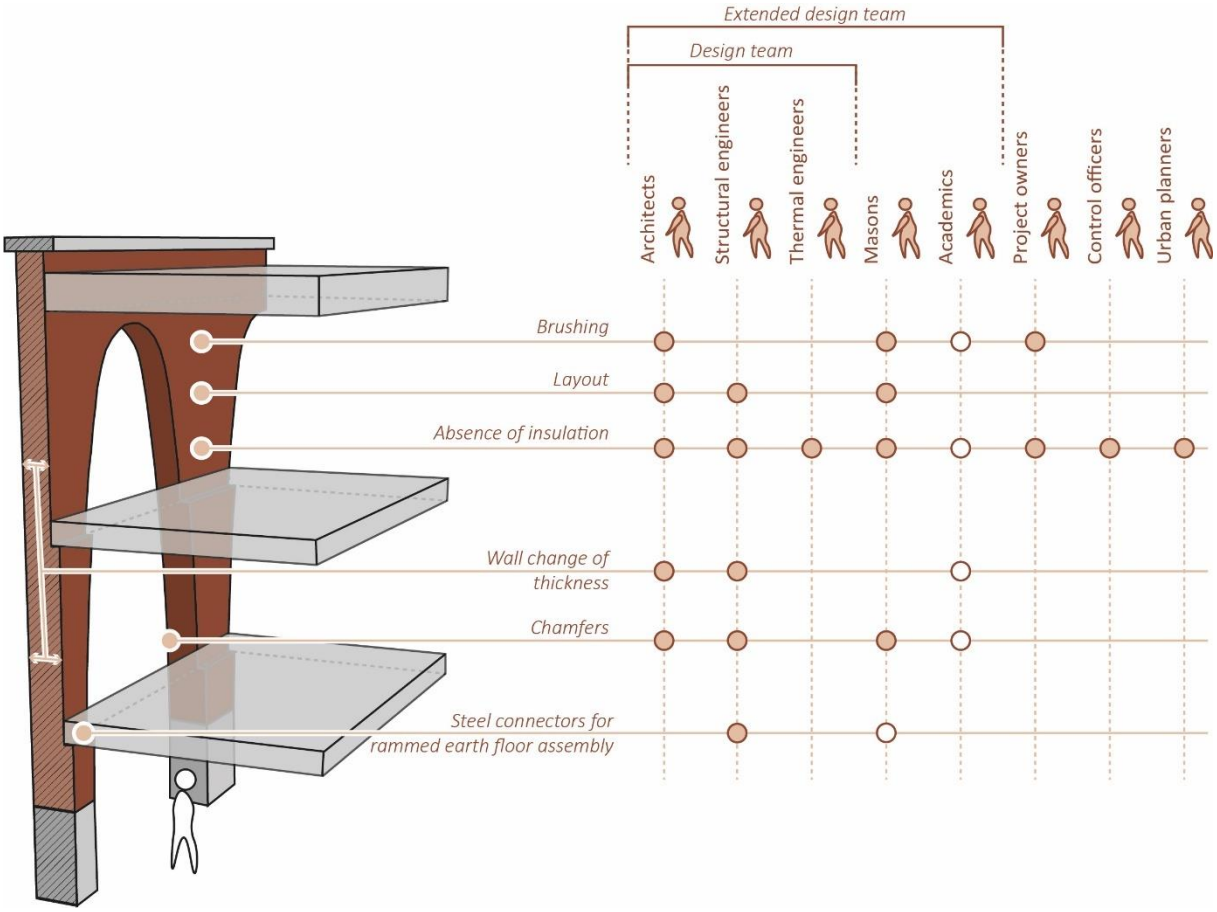

Figure 5.69: figure representing the involvement of the different stakeholders in the technical decisions. The white circles referred to the stakeholders that have first pointed out the proposition when it was possible to identify. The element of the wall is represented before the end of construction, which is why joineries are not depicted (source: author)

4.2.2. Assemble a qualified team where trust was shared

Another key to success that was identified during the interviews was the trust-based relationship between the stakeholders, particularly in the extended design team: Academics and masons were used to working together for decades, and the trust shared between the architect, the structural engineer and the mason was highlighted by the latter.

Goizauskas (2019) enlightened in his Master's Dissertation on the relationships of trust and their construction during the project. From an anthropological point of view, he followed the project in the construction phase and studied the relationship between the various stakeholders, particularly during the ATEx process. He has expatiated how the relationship of trust made it possible to override the ATEx refusal and to carry out the project. He also explored the non-standardised know-how on earth construction of the various stakeholders, in particular the masons, that contributed to building these relationships of trust (Goizauskas, 2019, p. 97).

The skills and notoriety of various stakeholders were also a means of consolidating trust. In particular, the control officer was reassured by the fact that the structural engineers were accompanied by academics:

> *"[The academics] were behind the structural engineers.* ***We were reassured by the intellectual quality of the project****." R05 – Control officer*

This team has come together around various motivations.

4.2.3. The different motivations of the stakeholders

The involvement and motivation of the various stakeholders seem to have been one of the keys to the success of the project. It is therefore interesting to look at the motivations of the various stakeholders in this project which were identified during the interviews. These included reputational interests, related to long-term investments, feedback experience, or finally political conviction and passion.

4.2.3.1. Reputation interest

Different interviewees have raised the question of the preservation or positioning of their reputation through the project, in particular the project owner, the thermal engineer, the academic and the structural engineer.

The project owner revealed the posture of the office in the construction sector by arguing to try to be a "*virtuous*" structure with an environmental commitment:

> *"We try to be virtuous developers. In spirit, this building is a step in this direction. We know that the impact of construction is quite enormous in terms of overall carbon weight, so the idea is to see what we can do to reduce the impact of new constructions in particular." R03 – Project owner*

Having a project owner committed seems crucial while the client (here the project owner) has been seen as one of the main drivers among stakeholders in the literature. Indeed, Niroumand et al. (2013) analyzed a questionnaire survey among ICOMOS[137] members (763 responses, in USA, UK, Australia,

[137] International Council on Monuments and Sites

Iran, India and Malaysia). The authors found that all the respondents saw the client as a significant driver for the use of earth in construction (Niroumand et al., 2013).

In addition, for the design team (thermal engineers, structural engineers, and architects), this building was a great reference, arousing the interest of construction professionals, and helping these structures to position themselves in the field of new earth construction:

“That gives us a great reference” R06 – Thermal engineer

*“But it shakes things up. **It also allows us to make ourselves known for other projects because it's a project that has received quite a bit of publicity**. There are quite a few people who have become aware of it and found it relevant.” R08 – Structural engineer*

*"**It's true that now it's a building that attracts a lot of interest**. We've had a lot of visits, especially during the construction work. Even today, we are regularly approached by architects, engineers, young people... Some students have been through this building and it's an inspiration. Our colleagues are very interested in this building. **It's something that gives us a lot of satisfaction**." R07 – Architect*

Finally, the academic interviewed also pointed out a reputational interest in this building. Indeed, the academic laboratory involved in the project is historically located in the field of earth construction research. However, due to the growing interest in this field, in particular in high-income countries for the low environmental impact potential of earth materials for construction (Marsh and Kulshreshtha, 2021), more and more academic laboratories start to study earth construction. This was described by the interviewee as an increasingly competitive sector, where following such a project helps to maintain a rank:

---

*"**There was an interest in visibility**. The [name of the laboratory] has historically been visible in the field of earth construction, but it remains so, thanks in particular to this project. Because you have to understand that today there are other laboratories involved in earth construction that are vying for the same position [...]. [...] All this means that mapping earth*

construction research is much more complex today. And much more competitive than it was 20 years ago... Or even 10 years ago. And so, with projects like this, it allows [name of the laboratory] to stay in the race." R01 – Academic

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To illustrate the interest that the building has aroused, Figure 5.70 has gathered some press articles on the building found on the internet. Of course, not having identified reputation interests among the other stakeholders during the interviews does not mean that they did not have reputation interests either.

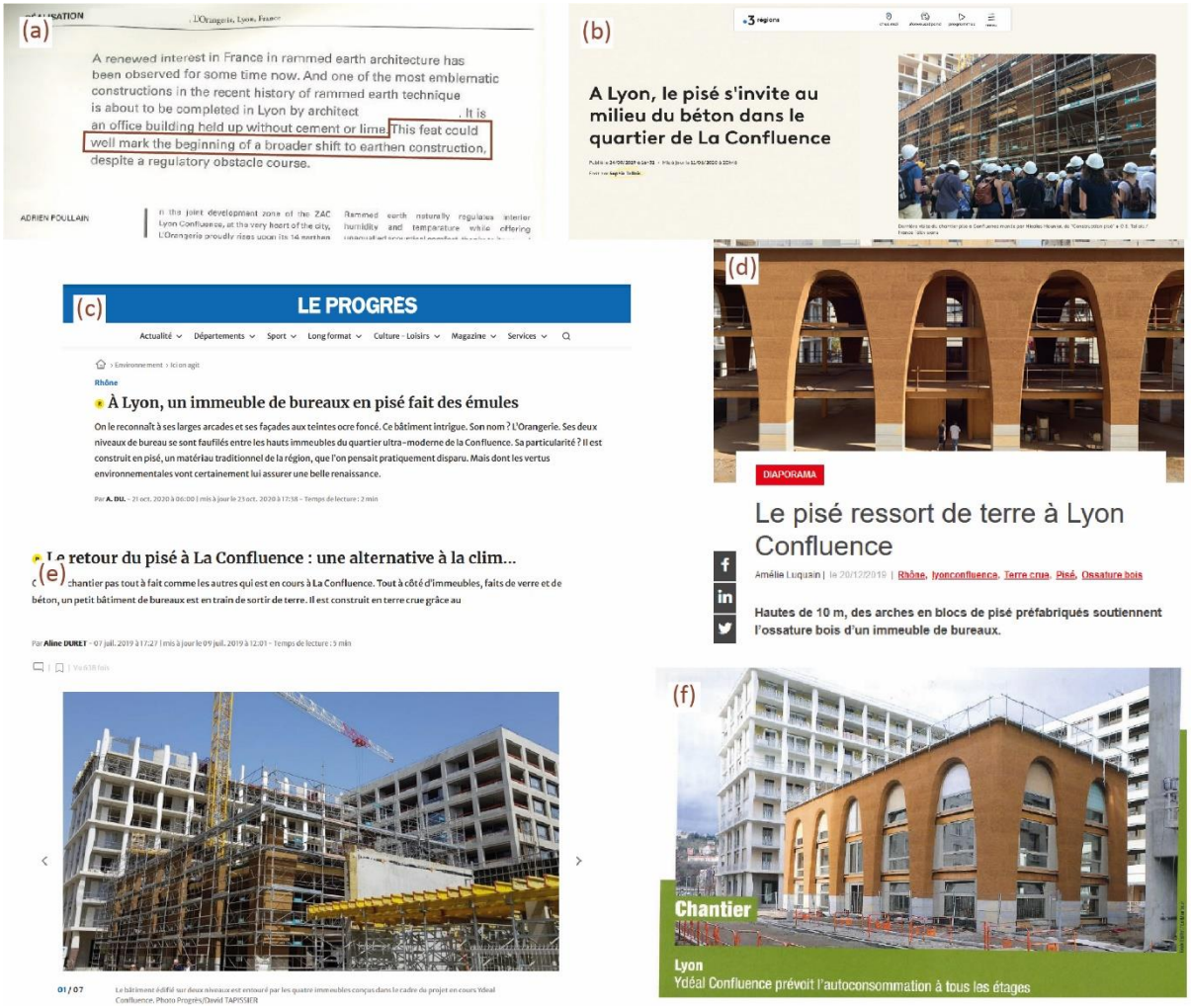

Figure 5.70: Extracts of press articles covering the case study: (a) Architecture specialised press article by Adrien Poullain 2020 (source: A'A' n°435) (b) Local press article by Sophie Tallois in September 2019 (source: France 3 régions) (c) Local press article by A.DU in October 2020 (source: Le progres) (d) Specialised press article by Amélie Luquain, in December 2019 (source: Le moniteur) (e) Local press article by Aline Duret, in July 2019 (source: Le progress) (f) Specialised press article by Emmanuelle N'Haux, in March 2020 (source: Le moniteur immo).

The reputation interests are from two sources that can be combined: pioneering role and visibility in promoting environmentally friendly solutions. In both cases, this question of notoriety goes hand in hand with long-term interests.

4.2.3.2. Long-term investment

Different interviewees expressed their long-term interest in this project. For instance, academics have been willing to work with structural engineers because of possible future research collaborations:

> *"We had the prospect of research collaboration with Batiserf" R01 – Academic*

Additionally, as already depicted in the previous section, this building represents a “good reference”, that could help the stakeholders (in particular the design team and the project owner) to obtain further contracts on similar projects.

Finally, it was also a way to gain expertise on the material that could be useful for later projects:

> *"The whole point of [name of the thermal engineer office] was to break new ground in areas that we can pass on to other projects" R06 – Thermal engineer*

The latter revealed the feedback that the project represented and which was highlighted by most of the stakeholders.

4.2.3.3. Feedback

The control officer considered that the experience feedback explained why this project was important for all the stakeholders:

> *Do you think the project will provide experience feedback?*
>
> *R04 – control officer:*
>
> *Yes, absolutely. That's why this project was so dear to everyone's hearts.*

In particular, the building represented an interesting feedback experience for the thermal engineer because the thermal monitoring of the building was a source of motivation:

> *"And the opportunity to thermally monitor the building, to really understand how it worked and because we believe in this material and think it's an interesting adaptation solution... The fact that it's going all the way,* ***that it offers opportunities for instrumentation, feedback*** *etc...* ***Of course, that was a major source of motivation for us****." R06 – Thermal engineer*

In addition, the control officer insisted on the need for the project to be exemplary. If the building had ultimately been bad experience feedback, it would have been a shame for the field of earth construction in France. This was a way for the control officer to justify the need for timber posts (as described in section 2), but also the high level of requirement in the control of the building and its structural justification, which will be described in the next chapter.

> *"Why did we do it? [Request the addition of timber posts]* ***Because it was totally unacceptable, totally impossible for us to be over-confident****. Because if, at the end of the day, this project isn't exemplary, if we don't get this feedback, if we get negative feedback, that's it for raw earth construction for 50 years." R04 – Control officer*

And in the end, this high level of requirement in terms of quality control, and the ATEx procedure were seen, by the structural engineers, as means for improving the process developed for the project and of increasing their knowledge and skills on rammed earth material:

> *"For me,* ***the quality control and the ATEx processes added value****.* ***It forced us to go further in formalising*** *[...], to ask questions, to provide answers and sometimes to deal with problems that we would have left under the carpet because we thought it was a non-issue. [...] So we went a lot further, we learnt a lot of things, and we will know how to do things better in the future." R08 – Structural engineer*

Reputation, long-term investment and experience feedback were therefore motivations to pursue the projects for the different stakeholders. But the latter gathered around a common desire to build a showcase building.

4.2.4. A common desire to build a showcase building

While the different stakeholders had different motivations and interests related to the project, as described above, they came together around the common desire to realize a showcase building. Indeed, during an interview, the mason highlighted the pleasure to build an exceptional project. Similarly, various stakeholders, including the project owner, the architect, and the control officer, noted the demonstrative aspect of the building:

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*"It was a building that was supposed to be **a demonstrator** and perhaps inspire other achievements behind it." R07 – Architect*

"This building had to be built. It had to be built with that look, with that architecture, so that people could say: it's possible to make modern buildings out of raw earth. Until this building, it was impossible to believe such a thing" R04 – Control officer

*"We really wanted to use rammed earth. We didn't want it to be just a cladding, we really wanted it to be the façade. We didn't really mind whether there were timber posts or not. **The idea was to achieve a showcase building from the outset.**" R03 – Project owner*

The quotation from the control officer highlights the correlation envisaged between showcase buildings and the improvement of the image of the material. Actually, the construction of showcase buildings is seen as a driver to improve the image and popularity among both professionals and clients whether in India (Kulshreshtha et al., 2020) or in the UK (M. S. Zami, 2021a). More broadly, it also has been underscored in the case of low-carbon building materials in the UK (Giesekam et al., 2016). Indeed, the latter, through interviewing industry leaders, showed that respondents considered showcase projects as one of the best ways to overcome “industry scepticism”.

Even if the will to make a showcase building seemed shared between the stakeholders, that should not mask the different *visions* of what should have been the showcase. Indeed, the quotation from the project owner above, underlines that having timber posts inside the building was not of great

importance to them, whereas, for instance, the structural engineer advocated not adding timber posts. This was confirmed in the interview with the project owner:

> *So, in your opinion, the various stakeholders wanted a showcase building, but with different visions of what a "showcase building" entailed?*
>
> *R03 – Project owner*
>
> *Yes, exactly. The structural design office wanted to show that it was possible to make load-bearing rammed earth with arches, so putting up timber posts, even as a precaution, didn't suit them.*

4.2.5. Conclusion of the section

This section describes teamwork, based in particular on the trust and motivation of the stakeholders, as a key success factor for the project. The stakeholders have coalesced around the desire to make a showcase building, with however different meanings under the *showcase* (giving importance to the load-bearing aspect or not). Their motivations were also explained by different interests that were put forward, including reputation, long-term investments and experience feedback. For other projects, this could be used as a means of clarifying the position of each stakeholder in order to stimulate collaboration, as recommended by Cripps (2004). Indeed, the latter also observed in the case of cardboard construction the various indirect benefits involved when conducting an innovative project: new skills; potential new products; new contacts (for future collaborations); advertising in existing markets; advertising in potential markets and building reputation (Cripps, 2004). All those indirect benefits were observable in the case study for the various stakeholders as a source of motivation to carry out the project. Identifying and understanding these interests when starting an earth project could help to boost motivation to pursue this project.

Although the involvement of all stakeholders was major, some were identified as key to the success of the project as discussed in the following section.

4.3. Key roles played by the stakeholders

First of all, although some stakeholders were more favourable (or even reluctant) than others for the final solution of the project (load-bearing rammed earth facades), in the end, none of them totally blocked the project. For instance, the structural engineer interviewed underlined that, although the project owners discovered rammed earth construction through this project and what such

construction techniques imply in the project process (see for example Chapter 6), they did not "*panic*" and found solutions as problems arose:

> *"Little by little they understood what was involved, and each time they [project owners] found solutions". R08 – Structural engineer*

Furthermore, although the control officers were considered reluctant to the use of load-bearing rammed earth (section 2.2.1), they nevertheless played a major role, particularly after the refusal of the ATEx procedure by agreeing to continue the project, as pointed out by the academic:

> *"**They did agree to let it happen. They could have refused**. If [Name of the control office] had refused, the project wouldn't have gone ahead. They had the final say. You have to realise that they agreed to allow an extremely innovative building to be built despite an unfavourable ATEx." R01 – Academic*

This was notably related to a hierarchical rise within the control office to the national technical director after the unfavourable ATEx. As envisioned by the structural engineers, this was the starting point of a discussion to find a compromise for the adoption of load-bearing rammed earth:

> *"**We had to deal with the national technical director from then on**, who wasn't present yet when we defended the ATEx. In any case, we hadn't had any discussions with him/her, and I don't think he/she was aware of the dossier at that time. And despite his/her very cautious stance and his/her lack of knowledge about raw earth construction, he/she began to take a serious look at the issues, asking us questions and asking for explanations... And he/she sets in motion an exchange of views, which we normally have with the design office, in order to reach an agreement". R08 – Structural engineer*

However, among the various stakeholders involved in the project, some were accounted for as key to the success of the project: the masons and the structural engineers. They were particularly recognised

for their skills in rammed earth construction. For instance, they were considered the rammed earth experts by the project owner:

In your opinion, who were the rammed earth experts for the project?

R03 – Project owner:

The experts were [Name of the contractor] and [name of the structural design office]

The skills and importance of these stakeholders were confirmed by most interviewees. In particular, the architect interviewed believed that he had the chance to work with this structural design office:

"We were lucky to be associated with [Name of the structural design office] from the outset, as they have the know-how, the power and the determination to see these projects through to the end." R07 – Architect

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In addition, the skills of the masons have been recognised by different stakeholders including the control officer, the academic and the architect. The latter emphasized the precision of the implementation by the mason:

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*"It was basically [Name of the mason] who built this and... **I think everyone pays tribute to him/her for this construction**" R04 – Control officer*

"I didn't think [name of the mason] was capable of such logistics. I mean, the Confluence site was impressive. [name of the mason] did something incredible." R01 – Academic

"It gave an incredible result, in terms of precision, his/her [the mason] team was... I mean, I've never seen anything like it. Over the length of the 32m façade, they laid blocks to within 2mm. So that's something you'd never come across with the shell companies you know." R07 – Architect

---

This highlights the important role played by the mason in the success of the project. Interestingly, it can also be understood as a revaluation of practical knowledge of the masons. And indeed, while asking what the main lessons learned would be for future earthen construction projects, the project owner underlined the importance of involving the mason upstream of the project:

> *"Well, maybe... and that's what we've done in this project... Maybe **it's to get the contractor involved upstream**. That is, right from the design stage **because it's the contractors that have the know-how about the methodology, about what they can do**..." R03 – Project owner*

The involvement of the masons upstream of the project, and more broadly the involvement of all the stakeholders, is indeed often recommended in the scientific literature, in the case of earth construction (Charef et al., 2021) but also more broadly sustainable construction (Häkkinen and Belloni, 2011). Furthermore, some authors, having studied the attitudes of structural engineers towards sustainability in the USA, think that structural engineers should indeed include themselves early in the design process so "*that the relevant technical considerations, as well as the conscience of the engineer, can inform the project goals at inception*" (Rodriguez-Nikl et al., 2015).

However, although the masons played an important role in the project and were involved early in the design phase, collaboration with stakeholders, particularly with the project owner, encountered difficulties. These challenges will be described in the next section.

4.4. Challenges related to the contractors

Three issues were raised from the data referring to contactor-related challenges: the lack of qualified professionals (as pointed out in section 2.1.2), taken under advisement as a risk by the project owner; the lack of habit to work with small companies; and the change in the balance of power.

4.4.1. Lack of skilled professionals: changing the power relationships

The lack of qualified professionals is sometimes cited in the literature as a barrier to the wider implementation of earth construction materials and methods (Ben-Alon et al., 2020a). In this region of France and for this type of building, there was indeed a lack of qualified professionals capable of carrying out the project at the time of construction. Only two contractors responded to the call for tenders: the one already involved in the design phases and another much more expensive than the first. Having only one contractor capable of continuing the project represented a risk for the project owner, as the thermal engineer interviewed pointed out:

> *"**One of the complicating factors was, as we made progress on the technical side, realising that there was only one company in the Rhône-Alpes region capable of doing this on this scale**, within a reasonable timeframe, etc. And that's what a developer hates to do: to contract with only one possibility of responding to the market. And that's what a developer hates to do: enter into a contract with only one possible supplier. It's a captive market. Having a very small number of contractors is really a factor of insecurity for project owners. If it goes bankrupt..." R06 – Thermal engineer*

In addition, various interviewees including the academic and the architect have recognized that having different contractors responding to the call for tenders is reassuring, particularly for the project owner, both in terms of the technical feasibility of the project and costs.

This lack of competition has changed the balance of power between the contractor and the project owner, the latter being dependent on the former for the success of the project. It was, in fact, a driver in negotiations to adopt the load-bearing rammed earth solution, whereas the masons had conditioned their response to the call for tenders: they only accepted the contract if the rammed earth was load-bearing the façades, similarly to the structural engineers.

4.4.2. Problems related to the contractor's capacity

The contractor company involved in the project was an artisan (i.e. very small company, less than 10 employees) that had low financial resilience given the building budget. Moreover, they were not used to dealing with such big projects, which made it difficult to quantify the cost. On the other hand, the project owners, who were not accustomed to working with artisans, did not initially reconsider the payment terms to account for the financial risk for the contractor and their need for upfront payment. Indeed, the project owners, more used to working with larger companies, pay its invoice after 45 days, which is the limit granted by the law. This was impossible in this case because the contractor's company was not able to make cash advances.

One solution adopted to reassure the client about the financial soundness of the rammed earth contractor was to bring together the various companies involved in the project (timber, foundation and rammed earth companies).

These issues did not block the project but created tensions between the stakeholders which could have been avoided by a proper contractualization between the project owner and the contractor, accounting for the problems of each. In his doctoral thesis, Gasnier (2019) proposes two ways to

facilitate the response of contractors to call for tenders: on the one hand, a correct dimensioning of the scale of earth construction lots according to the capacities of the current companies and, in the case of a large construction site (as for the case study), and a division of certain lots to allow several craft small enterprises to respond (Gasnier, 2019, p. 239). Grouping companies as it was done for the case study is therefore another solution.

4.5. Conclusion of the section

This section outlines the significance of teamwork, particularly founded on the trust and motivations of the stakeholders, as a key to the project's success. These stakeholders have converged around the aspiration to create a showcase building, yet with distinct interpretations of the term "showcase". Their incentives were also driven by varying interests, encompassing reputation, long-term investments, and insights from past experiences. In the context of different projects, this approach could serve as a tool to elucidate each stakeholder's stance, fostering enhanced collaboration. In this teamwork, all stakeholders had major roles but the structural engineers and the masons were seen as key to the success of the project, by the other stakeholders. Concerning the latter, this could be seen as a valorisation of practical knowledge in the design phase. Challenges were also related to the involvement of the masons. Indeed, the lack of skilled contractors in the region was perceived as a risk for the project owners and changed the balance of power between masons and project owners. On the contrary, the payment terms of the project owners represented a financial risk to the contractor. Improving the collaboration between these stakeholders could increase understanding that might help overcome related challenges.

5. Conclusion of the Chapter

From the definition of barriers and drivers provided at the end of Chapter 4 (barriers refer to what makes it difficult, while drivers to what facilitates, consensus reaching), this Chapter has described what can be considered as barriers and drivers in the case study. The first barrier was the constant questioning of the load-bearing rammed earth wall, either by questioning the use of rammed earth itself (with a counterproposition of using poured earth) or by questioning the load-bearing capacity of the rammed earth walls (by adding a timber structure or wood pillars). The controversy around the choice of rammed earth against poured earth raised from a conflict between two teams of stakeholders carrying each proposition. It underscores the importance of having all stakeholders convinced of the technique as early as possible in the design. However, this conflict had the advantage to raise various issues about the use of rammed earth that then had to be addressed: particularly, the erosion management and the lack of possible competition between different propositions answering the tender files, due to a scarcity of contractors. The project owners required the two teams to

investigate both propositions in parallel, with a particular focus on the cost of each and the potential necessity of an ATEx procedure, which highlight some of the project owners' concerns. Finally, the poured earth proposition was rejected at the end of the detailed design phase. However, the load-bearing capacity of the rammed earth was then consistently questioned until the delivery of the building. Indeed, due to a lack of approved standards, a lack of scientific evidence, and a lack of confidence either in the load-bearing rammed earth or in the design proposed, or both, control officers requested an ATEx procedure. Such a procedure was unwanted by project owners and design time because it represented additional costs for the first and considerable work for the second, in particular for the masons and the structural engineers that built the ATEx report. Moreover, this procedure represented a risk in case of rejection of the report as it would probably have meant additional insurance costs for the project owner. And actually, the ATEx report was finally rejected for two main reasons a too-small safety factor and a lack of justification for the absence of creep for rammed earth. These two issues will be discussed in the next Chapter.

The rejection of the ATEx could have blocked the project, however, it still continued as the control officers decided finally to provide their opinion on the project without passing by the standards organization which delivers the ATEx. This decision might be explained by a scale-up in the hierarchy among the control office, allowing them to take responsibility for the risk. Additionally, at the rejection of the ATEx, the construction of rammed earth blocks already started so there was no possibility to change the design. This highlights the crucial role played by control officers in the case study, representing both barriers and drivers at different moments of the case. This paragraph illustrates the barriers encountered by design teams when designing unstandardized (meaning no approved standard) materials, particularly when these are load-bearing. Indeed, control officers questioned the load-bearing capacity of the rammed earth façades by proposing the addition of timber pillars. This might mean that non-load-bearing rammed earth façades would have been acceptable. This underscores the necessity to consider different load-bearing and non-load-bearing materials when investigating barriers and drivers, that could be incorporated into the object definition.

While the load-bearing capacity of the rammed earth was a major point of discussion, other aspects of the wall’s design were also subject to debate, both related to the water sensitivity of the earth, namely: the erosion management and the potential need for insulation. The water sensitivity and the related supposed low durability of the material are often seen as a barrier to the use of earth in construction in the literature. In particular, this hypothetical barrier is often cited to justify making research on adjuvantation (Cuccurullo et al., 2022; Medvey and Dobszay, 2020; Vikas et al., 2023). However, the case study underlines that the justification of erosion management was not an important problem for designers. Indeed, thanks to practical knowledge of the masons and knowledge exchange

between the stakeholders, different solutions were swiftly found during the detailed design phase. For example, they used chamfering to treat the brittle angles of the rammed earth walls. Therefore, the case study analysis highlights that it might not be possible to see the supposed poor durability as a "main" barrier (in our case not a barrier at all) to the use of earth in construction. This illustrates once again the bias, introduced in Chapter 2, in the introduction of studies using barriers to justify their research question. Concerning the insulation, the debate stood longer than erosion management, until the request of the ATEx. Indeed, removing the insulation facilitated the development of the ATEx report as there was no need in that case to justify the interaction between the insulation and rammed earth, and in particular the risk of water accumulation was removed. Finally, the final technical choices resulted from a negotiated and collaborative process (more or less easy, more or less long) between various stakeholders, which highlights the importance of teamwork.

Indeed, the latter, based on the trust and motivations of the stakeholders, was seen as a key driver. The stakeholders have coalesced around the desire to make a showcase building. However, what was meant under the *showcase* was not consensual as some stakeholders put great importance on the load-bearing characteristic of the wall (masons, academics, structural engineers), while others just wanted to have a rammed earth façade, either load-bearing or not (project owners). Additionally, the motivations of the stakeholders included reputational interests, long-term investments and experience feedback. These can be seen as drivers to motivate stakeholders in using rammed earth for future projects. However, it should be noted that these interests have material conditions, indeed as shown in Chapter 4, the different structures involved in the design of the case study, were also involved in other bigger projects, bringing economic benefits. Therefore, as the case study was marginal in the economic benefits for these structures, they were materially able to find other interests. This was different for the masons, who had high economic constraints on this project, meanwhile played a major role. Indeed, along with the structural engineers, the involvement of the masons early in the design was seen as a key success factor. This could be seen as the valorisation of practical knowledge in the design phase. However, the masons (a small company) had not the economic conditions of the other structures. Therefore, the payment terms of the project owners represented a financial risk to them. On the contrary, the fact that only one mason company was able to build the project was considered a risk for the project owners as they became dependent on them. Improving the collaboration between these stakeholders could increase understanding that might have helped to overcome related challenges.

To conclude, the design and construction of the load-bearing rammed earth façades was the result of a long-negotiated process between the stakeholders, involving economic, social, organisational political and technical considerations, highlighted by the description of specific technical issues such

as the load-bearing capacity of the wall, the erosion mitigation or the use or not of insulation. During this negotiated process, the collaboration of all the stakeholders (project owner, thermal and structural engineers, architects, masons, academics, developers, and control officers) appeared to be one of the keys to the success of the project, although it also presented some challenges. This chapter addressed objective 4 “Identify obstacles and drivers encountered in a showcase rammed earth building project”.

This negotiated process, in particular between control officers and structural engineers, resulted in the implementation of a specific justification method, developed by the design team. This method will be the object of the last chapter and will make it possible to situate the research question and the results of the first chapter in the specific case study.

6 *Key steps to a performance approach of design: situating the assessment of compressive strength*

Chapter 6 describes the different key steps of the performance design approach adopted for the building: resource selection, characterization and quality control, in which compressive strength played a crucial role (objective 5). These key steps can be seen as drivers as they helped the acceptance of the load-bearing rammed earth façades (objective 4). This chapter is first introduced by situating this approach and by highlighting some political implications related to it. However, it is not a question of analysing these political implications, but only of highlighting them for the sake of transparency and reflexivity in order to situate the method proposed in Chapter 1 in socio-political realities. Therefore, this chapter ends with a reflection on situated knowledges theory for civil engineering research, in particular by proposing an autocritique of the introduction of the article published from the knowledge developed in Chapter 1.

Parts of this chapter will be published under:
Pelé-Peltier, A., Goizauskas, J., Under review. Toward a situated understanding of challenges in the design and construction of circular raw earth buildings: the case study of a rammed earth office building in France.

1. Introduction

While Chapter 5 describes the design and construction challenges from a broad perspective occurring during the project, this chapter will focus on the process of justifying the load-bearing rammed earth façades, in particular the process of justifying the compressive strength. Indeed, Chapter 5 highlighted the important debate that occurred around the load-bearing capacity of the wall and therefore the importance of compressive strength in the project. Following the definition of the barriers and drivers that have been established for this thesis at the end of Chapter 4, this justification process can be considered as a driver that made it possible to convince all the stakeholders to accept the load-bearing rammed earth façades. Therefore, this chapter completes the Chapter 5 in addressing objective 4 (Identify obstacles and drivers encountered in a showcase rammed earth building). Then, from the perspective of the theory of situated knowledges, this chapter aims to situate the method developed in Chapter 1 (that addressed objective 1) in this process of justification, itself situated in a normative system with socio-economic and political implications (Objective 5).

Thus, the philosophy of the method employed by the structural engineers, based on Eurocodes[138], will be described and situated among other approaches. First, the potential need to create new standards will be discussed to highlight socio-political implications for different groups of stakeholders. From this, some insights on the different socio-political implications according to the philosophy of the method chosen will be provided. The method of design-by-testing used by the structural engineers will then be described, emphasizing that other approaches exist (Appendix E). It should be noted, though, that the purpose is not to analyse the consistency of the design method (assumptions and calculations) but only to make visible that the choice of the design method and related research will have socio-economic and political implications. This is important in the case those are taken as the basement to producing new standards. Then, the key steps of the design method including materials sourcing, prototyping, characterizations, prefabrication and quality control, will be analysed, spotlighting the collaborative work between the different stakeholders of the case study. This will allow us to situate the method developed in Chapter 1 among these key steps to finally develop a discussion on situated knowledges for civil engineering research, from the case of earth construction.

[138] The Eurocodes are a set of European standards for the design of civil engineering structures and construction. They were developed by the European Committee for Standardization (CEN) to harmonize and standardize the design and construction practices across Europe. The Eurocodes cover various aspects of construction, including structural design, geotechnical engineering, fire safety, and more. Each part of the Eurocodes provides specific guidelines, formulas, and methods for designing structures to ensure their safety, reliability, and durability. They are essential tools for engineers and architects when designing buildings, bridges, roads, and other infrastructure across Europe.

2. The philosophy of the design method employed: a performance approach with socio-political implications

2.1. If there is a lack of standards, should new ones be created?

As explained in Chapter 2, a significant body of literature argues that the lack of standards could act as a barrier to the use of earth in construction, especially in high-income countries (Ben-Alon et al., 2020a; Leylavergne, 2012; Morel et al., 2021b; Van der Linden et al., 2019b). One could therefore argue that it is necessary to create new standards for earth construction. However, in Chapter VII of his PhD (pages 377 to 416), Victor Villain offers some perspectives on this issue in the French context.

Indeed, as this author has already described that different prospects for the development of earth construction exist according to the professionals, these differences are also found in the prospects for the creation of new standards, particularly in the case of implementation standards. By analysing a standardisation process that took place in France in the last decade, led by a working group of professionals wishing to establish new standards (named "professional rules"[139]) on earth construction, V. Villain describes two visions among professionals. The first is the wish to create new standards to bring earth construction into mainstream construction, arguing that standardisation would make earth construction more economically viable, facilitate insurability and provide technical references for training. The second is to be sceptical of the need for standards, arguing that standardisation would restrict the possibilities for earthen construction by standardising the implementation fostering the use of standardised material instead of on-site manufacture with local soils (Villain, 2020, pp. 401–402). The latter might explain the reluctance of some professionals toward standards creation, as it was observed in the US and considered a *barrier* by some authors (Ben-Alon et al., 2020a).

These opposite visions are also found at the international level. Indeed, Tayyibi et al. (2016), by comparing six national codes and regulations, conclude that "each code or regulation is influenced by the specific country's context" (Tayyibi et al., 2016). They illustrate this conclusion with two countries having different approaches: India and Morocco. The first targets industrialization, while the second is more conservative, according to the authors but without further describing what a vision of industrialization would mean compared to a conservative vision.

This underlines that the creation of standards has, in essence, socio-political implications exacerbated in the case of earth because of the potential non-industrial approach of the technique. It is interesting

[139] "Règles professionnelles" in French. The first level of standards, scope: the implementation, that are approved by the AQC

therefore to look at some implications according to the approach chosen, namely performance or method-based approaches.

2.2. Performance-based requirements, method-based requirements or mixed requirements

As Mariapia Angelino defined in her Engineering Doctorate thesis, different types of technical provisions in the standard must be considered: *requirements*, which imply mandatory provisions, and *guidance*, which is therefore optional and indicative for the designers. The requirements "*convey criteria to be fulfilled when adopting that specific standard*" (Angelino, 2019, p. 37) and can be of different nature: performance-based requirements; method-based requirements or mixed requirements. This section will provide definitions along with the advantages and disadvantages of each.

2.2.1. Definitions

The performance approach, as defined by Foliente (2000), is "*the practice of thinking and working in terms of ends rather than means."*. This can be applied to establish a design philosophy as defining criteria in terms of performance objectives, which will be considered in order to design an artefact[140]. Standards following the performance approach, therefore, describe requirements for outputs or outcomes rather than specific methods to be used (Angelino, 2019, p. 233). Thus, the methods for meeting these requirements may vary. On the contrary, the method-based approach[141] will establish requirements for the methods (processes, specific inputs, or activities).

A standard based on a performance approach requires addressing different issues, as described by Angelino (2019, p230), such as defining what is considered as performance and what are the requirements accordingly[142]; how the fulfilment of these requirements will be verified (quality control[143]); and what are the consequences if the requirements are not met.

Typically, standards are not purely defined by performance-based requirements. For instance, the Eurocodes present, what Angelino (2019, p236) calls, "*mixed performance-based requirements*", meaning that requirements are defined in terms of purposes, but rules and guidance for achieving these requirements are also provided.

[140] Angelino (2019) defined in her EngD thesis "artefacts" as "an engineered entity with varying degrees of complexity, from a manufacturing product (e.g. concrete or steel) to an infrastructure system" (Angelino, 2019, p. 230). In our context, the artefact that will be considered is therefore the element of wall described in chapter 4.
[141] Also called prescriptive approach
[142] See section 4.3. of this chapter
[143] See section 4.5. of this chapter

2.2.2. Advantages and disadvantages

Different advantages and disadvantages exist according to the type of standards (prescriptive or performance approach). The advantages of the performance approach include facilitating innovations (Foliente, 2000), offering more flexibility to designers, allowing different methods to be used to achieve the requirements (Henderson, 2006), or obtaining a better quality of the final artefact as professional experience is needed (Angelino, 2019, p. 232). As described by Henderson (2006) in the case of straw bale construction in the US, professionals also appreciate the performance approach because it leaves them with more decisions to make and therefore more responsibility. However, it also presents different disadvantages like increased engineering costs, difficulties in performance control, or specific skills required in the design team (Angelino, 2019, p. 232). On the contrary, the prescriptive approach simplifies the design and construction (Henderson, 2006) and represents a limited risk because it is "generally based on methods that have proved to work in the past" (Angelino, 2019, p. 232). However, the prescriptive approach "*may prevent or discourage users from proposing more cost-effective or innovative solutions*" (Angelino, 2019, p. 232).

It is because the pure performance-based approach represents different issues that Angelino (2019) argues for 'mixed' performance-based requirements and provides the following advice:

> *"Standards should be developed to provide clear requirements for competent practitioners. As a result, the performance requirements (or design objectives) should be accompanied, where possible, by methods as a means to meet the requirements, and the methods should be clearly presented as advice, i.e. recommendations or permissible approaches." (Angelino, 2019, p. 236).*

From these advantages and disadvantages, it is understandable that the choice of approach will have socio-political consequences. For instance, as discussed previously, various levels of expertise are needed according to the approach, therefore it could be assumed that choosing the performance approach would make necessary the development of specific training associated, having, therefore, political implications (who should follow this training? How to finance it? Etc.). More insights will be given in the following section on the potential implications in the case of earth construction in France.

2.3. Implications in earth construction of the choice of type of requirements

This section will discuss some of the implications in earth construction of choosing between performance-based or method-based requirements, including political, technical (in particular, linked to heterogeneity of earth material) and market implications. This section is not intended to exhaustively explore the relationship between socio-economic implications and the choice of type of standardization, but merely to provide some illustrations so that the reader understands that all types

of standards are socio-technically integrated, which highlights the necessity to situate the approach. Normative and regulatory systems as socio-technical systems will therefore first be described.

2.3.1. Normative and regulation systems as socio-technical systems

As with buildings (see Chapter 3), normative and regulatory systems can be considered socio-technical systems (STS), and research in Science and Technology Studies can be used to describe them. For instance, Meacham and van Straalen (2018) developed an STS framework to analyze building regulation and investigated the challenges and ways to overcome them in incorporating risk into regulation. Some other authors consider the use of a STS framework as an effective analytical tool in construction (see for example (Rohracher, 2001) for a proposal of a socio-technical perspective useful for managing a technological transition towards construction sustainability). However, Meacham and van Straalen (2018) have highlighted that "many stakeholders in the building regulatory process still view building regulations as largely technical documents, and do not always consider social and institutional infrastructure, roles and expectations" (Meacham and van Straalen, 2018). The lack of appreciation of the socio-technical complexity of building regulations has been described as contributing to failures in the regulatory system (Meacham and van Straalen, 2018).

Therefore, the way building regulations and standards are designed will necessarily have socio-economic implications and vice versa. As an example, the concept of "regulatory capture" can be cited, referring to "situations for which regulations benefit particular private interests rather than provide the broader public benefit that the regulations are intended to promote" (May, 2003). Prescriptive approaches are particularly prone to forms of localized capture because they promote the use of particular products or technologies. On the contrary, performance-based approaches do not favour particular producers because no prescription of methods or materials is given, thus avoiding the "localized form of capture" (May, 2003).

Different socio-technical implications can be described in the case of earthen construction, including political implications and the question of the use of heterogeneous local material, which can also be soil waste from excavation works.

2.3.2. Political implications: questioning the role of artisans in the construction

There are political implications in creating standards. As already mentioned in Chapter 2, Victor Villain described in his PhD thesis the different development perspectives that exist according to the political thinking of professionals, in France. While the development of regulations and standards is generally seen as a driver for earth construction (Marsh and Kulshreshtha, 2021; M. S. Zami, 2021b), their development could reflect the political views of the different stakeholder groups, as described by

Victor Villain. Moreover, the evolution of standards can be perceived as a threat to "craftsmanship" by some earth construction professionals (Ben-Alon et al., 2020a), or, on the contrary, as an opportunity. Indeed, Jean Goizauskas, who is currently preparing his PhD thesis in Science and Technology studies (Goizauskas, ongoing), wonders, in the process of institutionalization of the field of earthen construction in France, how certain groups of professionals defend their political vision of building practices. He analyses how a performance-based approach makes it possible for a group of professionals in earthen construction to defend the use of local natural materials and masons' related know-how and skills. Indeed, basing the development of a standard on the skills of artisans would increase their responsibility and ensure their role in the construction field which would requestion the current mainstream construction. Where masons are involved only in the construction phase, and sometimes disregarded (see for example (Jounin, 2009) as already mentioned in the introduction of this thesis).

And indeed, the guide of good practices on earthen construction, already mentioned in Chapter 4, produced by construction professionals was developed with a performance approach, as recalled in the introduction of the guide:

> *« This guide has been drawn up according to a **performance-based approach**, i.e. fixing the result to be achieved (characteristics, performance, etc.), thus allowing control, both in the design phase (dimensioning) and in the construction phase (on-site inspections). **The means to be used remain open** »*[144] *("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 8)*

Later in the guide, the importance of adapting to the resource and considering knowledge about the earth material is depicted as necessary conditions:

> *"The implementation has to be **adapted to each new earth** and **a knowledge of the material** is necessary to produce elements of the structure that can withstand the constraints and stresses that will be applied to it"*[145] *("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 16)*

[144] Translated from French to English by the author. Original version: « *Ce guide a été rédigé selon une démarche performancielle, c'est-à-dire fixant le résultat à atteindre (caractéristiques, performances, etc.), permettant ainsi le contrôle, aussi bien en phase d'études (dimensionnement) qu'en phase de réalisation (contrôles sur chantier). Les moyens à utiliser restent ouverts* »

[145] Translated from French to English by the author. Original version: « *la mise en œuvre est à adapter à chaque nouvelle terre et une connaissance du matériau est nécessaire pour produire des éléments d'ouvrage supportant les contraintes qui lui seront appliquées.* »

Other excerpts of the guide illustrate the importance given to the know-how skills of artisans by insisting on practice with the earth material:

> *« However, these guides are not pedagogical manuals and do not replace either training or learning, and the practice with the earth material remains the only way to acquire real skills."*[146] *("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 5)*

Therefore, there is a context of struggle between the interests or beliefs of different stakeholders which is found in the process of material standardization. This could constitute a barrier to obtaining a consensus in the creation of standards as explained by one of the interviewees, who considers two conflicting questions: industrial versus artisanal development and the use or not of hydraulic adjuvants.

So, why do you think there is a lack of standards today in France?

R02 – Third-party controller

That's a very big question, can we cut the recording? [Laugh] I don't have a religion. ***There are dissensions****. There were in the [field of construction with] straw too, and they overcame them. I'm going to try to remain perfectly impartial in the way I express myself.* ***There are 2 issues****.* ***There's industrialisation****: there are people who say "no, it's got to stay traditional, it's vernacular architecture", with local earth and so on. And then you have other people who say "yes, but if we want to develop, we need to industrialise", and that would require capital, big factories, the soil wouldn't necessarily be local...* ***And the 2nd issue is stabilisation****. Should earth be stabilised*[147] *or not? [...] I don't have a religion. Well, I don't have a religion to have. [...] Everyone has to work together, if possible, to find a consensus that will enable us to move forward and make rules that are proscribed. [...]*

[146] Translated from French to English by the author. Original version: « *Ces guides ne sont cependant pas des manuels pédagogiques et ne se substituent ni à une formation, ni à un apprentissage, et la pratique de la matière reste le seul moyen d'acquérir des compétences réelles.* »

[147] As already explained, in this PhD thesis I prefer the use of the term adjuvantation (in particular hydraulic adjuvantation) instead of stabilisation.

Interviewer:

So, it is a problem of lack of consensus?

R02 – Third-party controller

*I think so, yes. Because of these 2 issues**: artisanal vs. industrial and stabilized vs. unstabilized***

Therefore, this section explicated some dissensus and political struggles in earth construction field that explain difficulties in standard creation. Besides, the heterogeneity of the material is also considered an issue in this process of standardization.

2.3.3. Challenges to using a local heterogeneous natural material

The earth material is a heterogeneous natural material which makes the process of creating standards difficult for nonconventional, and vernacular materials more broadly:

> *"In many cases of conventional construction materials, engineered materials specifications (or standards) result in standard (or standardized) materials and building products. However, when it comes to nonconventional and vernacular construction materials,* ***the emergence of standard materials from engineered building standards is often challenged by their high variability and their reliance on local or traditional construction methods****" (Harries et al., 2020)*

As explained by Harries et al. (2020), various strategies can be adopted to address this issue. In France, the guide expresses the desire to adapt to the local earth material, which is supported by some researchers (Morel et al., 2021b). Thus, the guide recommends characterizing, and therefore applying the requirements, on the earth used (i.e. the earth building element such as rammed earth walls) rather than on the raw material:

> *« It is, therefore, necessary to characterise not the raw material, but the building element implemented"*[148] *("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 16)*

[148] Translated from French to English by the author. Original version: « *Il convient donc de caractériser non pas la matière première, mais l'élément d'ouvrage produit.* »

This point of view is supported by some researchers as highlighted by the academic interviewed for the thesis:

> *"We do not know how to link the structure performance to the raw material" R01 – Academic*

In this sense, the problem of heterogeneity of resources would be partially overcome by the use of performance-based standard-setting requirements on the implemented construction element rather than on the raw material, which would therefore mean the need to test the implementation rather than the material. However, as the standards organisation employee interviewed highlighted, assessing the performance of local materials is not an easy task:

> ***Using a material that comes from less than 20km around the site, which is an understandable and relevant objective from an environmental point of view, is very complex. How do I know what performance this local earth will give me?*** *For certain subjects, this is not a problem, but if, for example, we start talking about creep... Obviously, we cannot test the earth for a year if the worksite has already started. R05 – standard organisation employee*

According to Harries et al. (2020), the heterogeneity of material from one location to another complicates the process of assigning specific numerical values that characterize the standard-development process. A "homogenization approach", like that used in timber codes and standards, could be used for earth construction. This approach would involve grouping different species or classes of earth materials to establish common guidelines (Harries et al., 2020). However, such an approach would imply being able to relate the properties of the raw earth to the properties of the earthen construction elements used, which is not an easy task. Some authors have initiated a similar approach insisting that this could help, but should not be a mandatory approach to allow innovation (Rojat et al., 2020) that is necessary to cope with the high level of a variety of soils and the imperative reduction of transportation. Indeed, it is known that transportation is the main environmental impact of earth construction, along with cement or lime adjuvantation (A. Ventura et al., 2022).

Therefore, creating standards for earth construction is also challenging due to the heterogeneity of the material, in particular, if there is a will to keep the possibility of using any local earth.

2.3.4. Earth is not a product

The approach that will be described later in this chapter through its key steps (selection of materials, characterization, etc) was described as unusual in conventional construction in France by two interviewees. This is due, in particular, to the fact that there is no "product" of rammed earth construction element[149]. Indeed, when asking the structural engineer if this approach was unusual, the answer was:

> *"Yes. Because usually you go to a material supplier, or you place the order with the suppliers and then you get the materials and the associated technical data sheet. In this case, we can be a prescriber. We know that the material is available, we know what our material is at the time of design and we don't need to take any steps upstream or order in advance." R08 – Structural engineer*

This is what the thermal engineer also described when speaking of "*a culture*" of the construction sector, turned upside down by the absence of earth products:

> ***"There is a culture in the building industry today of buying materials from a catalogue, which has an impact on the whole building production chain.*** *Amongst developers, there are buyers. Their job is to buy materials from a catalogue and negotiate contracts. And it's the same all over France. And in fact, the use of bio-sourced materials [or raw earth] destroys the structure, they don't know how to deal with those materials. » R06 – Thermal engineer*

Thus, while contractors are usually expected to assemble products that are already defined, in terms of performance, in the case of earth construction and in particular rammed earth, contractors produce

[149] Products should be understood as elements of earth construction that are produced off-site and then sell to the builders for assembling on-site. A few producers exist in France, for instance *Cycle Terre (https://www.cycle-terre.eu/)*, located close to Paris, produce CEBs or bag of earth intended for mortars or coatings. In Europe, Claytec can be cited https://www.claytec.de/en. For the case of rammed earth, Martin Rauch could be considered as a rammed earth wall producer (https://www.lehmtonerde.at/en/products/product.php?aID=70) where wall of rammed earth are built at the factory and then transported on-site. However, one should be aware that transportation is one of the most impactful parameter on earth construction in term of GHG emissions (A. Ventura et al., 2022). Moreover, those approaches has been described as being potentially having a lower circularity (Pelé-Peltier and Goizauskas, Under review).

the rammed earth from the raw resource. Section 4 will spotlight that it places the masons at the centre of the approach adopted for the building (and in the method proposed in Chapter 1). Besides, considering earth products can create problems, in particular in the availability of local resources. Indeed, the lack of suitable local resources already has been considered for the case of CEB production (CEB being the earth product) as a barrier, forcing professionals either to take non-local earth or to adjuvant it with lime and cement (Dorado et al., 2022), which both significantly increase the environmental impact (A. Ventura et al., 2022). However, this "barrier" to CEB stems from considering first what technique will be used, and here which product will be produced first, before considering what is the local resources and suitable techniques.

2.4. Conclusion of the section

Thus, this section has highlighted the political and socio-technical implications of standardisation systems. Particularly, it has been emphasized that dissensus exist among professionals on which philosophy should follow new standards for earth construction. Differences between performance or prescriptive approaches have been described. In particular, it has been spotlighted that the performance approach could be used to secure the (important) role of artisans in the building process. On the contrary, it can be assumed that the way the new standards will be created, could reduce the current important role played by the masons (as highlighted in the last section of Chapter 5). This underlines once again the need to situate our research because it can have consequences in these debates between professionals, particularly if this research is used for new standard creation. In that sense, it is a matter of responsibility as researchers.

3. Design approach: design-by-testing

This section aims to define the design approach adopted for the studied building focusing on the definition of the design compressive strength of the rammed earth wall, as it was one of the main parameters used for the design. Once again, the purpose is not to analyse the consistency of the design method used (the assumptions and calculations). In this section a definition of the design by testing approach will be provided followed by the method chosen for the project and finally, insights will be provided on the safety factor for earth construction.

3.1. Definitions

Due to the great variability of earth material from region to region, it is considered almost impossible by some authors to specify "*a standard or generalised compressive strength*" (274-TCE, 2021, p. 134). In addition, the compressive strength depends on many parameters including intrinsic parameters, such as clay content and activity (Champiré et al., 2016) as well as implementation parameters, such

as dry density (Abhilash and Morel, 2019). The latter depends on manufacturing water content and compaction energy (Morel et al., 2007). Therefore, one way to obtain compressive strength in the case of a construction project is to carry out tests.

The design-by-testing approach is defined in the Eurocode as follows:

> *"Design assisted by testing is a procedure using physical testing (e.g. models, prototypes or in situ) for establishing design values. Such procedures can be used in particular for those cases where the calculation rules or material properties given in the design Eurocodes are considered insufficient, or where a more economical design may result" (Gulvanessian et al., 1997, p70)*

Therefore, in such an approach applied to the compressive strength, the idea is to test the *performance* of the material to establish a compressive strength value, which must additionally be achieved by the building element and therefore verified (through quality control for instance). The design-by-testing can be called a performance approach, the requirement being the design value of the compressive strength which must always be greater than the loads applied to the wall.

3.2. The method chosen in the project: based on Eurocodes

The design method developed by the structure design office was based on the use of Eurocode 0 (*Eurocode 0 - français*, n.d.). The earth material not being covered by Eurocodes 1 to 9, designers are supposed to refer to Eurocode 0. The latter covers all types of materials and provides the basis for the calculation of structures with the Eurocodes (H. Gulvanessien, 2001). In particular, a performance-based approach is given in Appendix D: "Design assisted by testing" (Gulvanessian, 1997). Design assisted by testing aims to determine "*the characteristic or the design value of a single material property or a resistance model from tests*." (Gulvanessian, 1997).

According to Eurocode 0, there are two methods to determine the design values of a material property. Either by evaluating a characteristic value, based on tests, which is then divided by a partial factor and multiplied, if necessary, by a conversion factor, or by directly evaluating the design value considering the overall reliability (adopting therefore a test procedure explicitly or implicitly taking into account adjustment aspects) (Calgaro et al., 2013, p. 220). As the first method is recommended by the Eurocodes, the structural engineers decided to apply it. The formula for any design value X_d is defined as follows:

$$X_d = \frac{\eta_d}{\gamma_m}.m_X.\left(1 - k_{n,d}.V_X\right) = \eta_d.\frac{X_k(n)}{\gamma_m} = \frac{X_k(n)}{\gamma_M} \quad (1)$$

Where X is a mechanical property (Compressive strength, tensile strength, etc.), $X_k(n)$ is the characteristic value evaluated from n specimens, η_d is the conversion factor between the properties of the specimens tested in the laboratory and the reality on-site. It can correspond to the scale-effect (investigated in Chapter 1), γ_m is the safety factor considering the uncertainty on the properties of the material, while γ_M corresponds to the global safety factor applied to the material, m_X is the mean value of the property measured in the laboratory (for example mean compressive strength), $k_{n,d}$ is a coefficient given by the Table 6.17, it depends on statistical parameters such as the statistical distribution, the level of confidence targeted (for example in our case, the confidence level targeted is 95%: or fractile 5%), D2 EN[150] 1990 (Gulvanessian, 1997) and V_X is the coefficient of variation, which corresponds to the variability of the results. This can be calculated with the formula:

$$V_X = \frac{S_X}{m_X} \quad (2)$$

Where S_X is the standard deviation defined by:

$$S_X{}^2 = \frac{1}{n-1} . \sum (x_i - x_m)^2 \quad (3)$$

The method applied in the project was based on the design-by-testing approach, notably, testing in a laboratory of the compressive strength of the rammed earth. The statistical analysis, based on the compressive strength of 8 specimens of rammed earth tested at a dry state and 4 at a wet state[151], was carried out. Two conditions exist for the statistical evaluation: an identified sufficiently homogeneous population, is required as well as a sufficient number of specimens. There is no recommendation on the number of specimens required in Eurocode 0.

Table 6.17: $K_{n,d}$ values for the characteristic value at a 5% fractile. n corresponds to the number of specimen tests. V_X known corresponds to a known coefficient of variation while V_X unknown corresponds to an unknown coefficient of variation.

n	1	2	3	4	5	6	8	10	20	30	∞
V_X known	2.31	2.01	1.89	1.83	1.80	1.77	1.74	1.72	1.68	1.67	1.64
V_X unknown	-	-	3.37	2.63	2.33	2.18	2.00	1.92	1.76	1.73	1.64

To choose the partial (or safety) factor, EN 1990 recommends referring to the appropriate Eurocode "*provided there is sufficient similarity between the tests and the usual field of application of the partial*

[150] EN is for EuroNorm
[151] See section 3.3. Characterizations

factor"(Gulvanessian, 1997, p. 152). In the project, it was decided by the structural design office to refer to part 3 of the French national appendix of Eurocode 6 (namely, "*méthodes de calcul simplifiées pour les ouvrages en maçonnerie non armée*"[152]), dedicated to masonry structures, and therefore considering the rammed earth façades as a masonry structure of rammed earth blocks.

This appendix contains Table 6.18 presenting the various possible choices of the safety factor. The columns correspond to a level of control (the higher the control, the lower the safety factor can be chosen) and the lines correspond to the confidence level in the evaluation of the performance of the masonry units and the mortar (the higher the confidence, the lower the safety factor).

Table 6.18: Partial coefficient in part 3 of French National annexe of Eurocode 6, extract of a table available in NF EN 1996-3_NA, translated from French to English by the author

Material	γ_M		
	Level of control		
Masonry units of Category I, designed mortar	1.5	2.0	2.5
Masonry units of Category I, prescribed mortar	1.7	2.2	2.7
Masonry units of Category II	2.3	2.8	3.3

While safety factors are generally very high for earth materials (see next section), the structural engineers decided to take a partial safety factor of 1.5 for this project. They justified it by the high expertise of the masons, a field inspection of the prefabricated blocks[153], characterization of the material in a research laboratory (Compression tests, Drying tests …)[154], and a careful structural design of the building. Indeed, due to the loads applied on the rammed earth façades and this form of arches, the safety factor had to be optimized:

> *"We needed to push the material a little further than with the usual safety coefficients, which were very penalising. So, we took the most optimal coefficient." R08 – Structural engineer*

[152] In English: "Simplified calculation methods for unreinforced masonry structures."
[153] See section 3.5. Quality control
[154] See section 3.3. Characterizations

Finally, to design the building, the structural engineer chose to refer to the *dry* compressive strength for the service life. In addition, the construction phase was taken differently by considering the increase in compressive strength due to the drying process, and the increase in loads due to the different steps of the construction of the building (before or after loading the floors for example).

3.3. From characteristic to design compressive strength: safety factors

Nowadays, the philosophy of the Eurocode, based on semi-statistical analysis and particularly on the use of partial safety factors, is widely used in European countries. The partial safety factors take into account the various uncertainties, including, for the safety factor applied to the performance of the material: a lack of information on the nature of the statistical distribution, uncertainties relating to the size of the specimens, the properties of the material, etc... (Calgaro et al., 2013) A similar approach can be used for the design of rammed earth construction. This is considered an important aspect by some authors. Indeed, as stated by Schroeder (2018) "*an important aspect* [of standards] *will be to define partial safety factors for load-bearing structures made of earth building materials*". This importance was also highlighted by the case study, as one of the main reasons why the ATEx commission rejected the proposal was a safety factor considered too low.

Table 6.19 brings together different partial safety factors from regulations and literature for the earth material and other materials for comparison purposes.

Table 6.19: Partial safety factor for earth material and comparison with other materials according to the literature (source: author)

	Material	**Partial safety factor γ_M (applied to the characteristic value)**
Earth Material	Rammed earth	**3-6** (according to the level of control) (Walker et al., 2005), **3-5** ("Guide des bonnes pratiques de la construction en terre crue," 2018)

	CEB (Compressed Earth Blocks)	**1.75** (based on the variability of lab testing) (Müller et al., 2017)
	Cob	**2.5** (wet state, calculated from lab testing with a target design value of 0,1 Mpa) (Quagliarini et al., 2010)
	General	**6.7-8** (Schroeder, 2012), **3** (for interior walls) to **6** (for exterior walls) (Schroeder, 2012), **2.6** (New Zealand Standard (NZS), 1998)
Other materials	Bamboo	**1.5** (Chung and Yu, 2002; Kaminski et al., 2016; Yu et al., 2003), **1.5 to 2** (Paraskeva et al., 2017)
	Load-bearing straw bale	**1.82** to **2.51** (Faine and Zhang, 2000)
Eurocode	Concrete	**1.5**
	Masonry	**1.5** to **3** according to the level of control and the type of mortar (Table 6.18)

What emerges from this table is that the range of partial safety factors for the earth material is very wide, from 1.75 to 8. Moreover, in general, the partial safety coefficients of earthen material are quite high compared with other materials such as bamboo and load-bearing straw bales that can be considered as non-conventional materials such as earth.

3.4. Conclusion of the section

Finally, the structural design approach taken for the building was a performance approach based on testing. The characteristic compressive strength was then first established by assessing it on specimens in the laboratory, to define the design compressive strength by applying a safety factor. This established the requirement to follow for the on-site (i.e. the rammed earth walls compressive strength should be higher than the design compressive strength). Various key steps of this approach have been identified and will be described in the next section.

4. Key steps in this approach of load-bearing rammed earth design

From the interviews and document analysis, various key steps for the design of the building were identified, including materials sourcing, prototyping, characterization, prefabrication, and quality control (see appendix D). All of these steps were necessary for the performance design approach adopted for the building's design. It should be reminded, that case study analysis does not seek transferability (See chapter 3) and therefore, although these key steps could be useful for further load-bearing rammed earth projects, it does not mean that they would be necessary or suitable for any rammed earth building.

Some of these key steps will be discussed in comparison with H. Gasnier's PhD thesis (pages 233 to 239), which also proposed key steps for the design of earth buildings, in the context of using the resource of earth excavation as part of the Grand Paris project[155]. Although the information provided by H. Gasnier is interesting, his proposal was not dedicated to rammed earth but to earth construction in general, using different buildings as case studies. Some of the key steps highlighted in his thesis will therefore not be discussed in this section because they are relevant for a scale different from the construction project scale. For instance, he had identified training as a key step to facilitate the use of earth in construction, which is more a matter of sector scale than of project scale. Challenges and processes around these different key steps will be discussed in this section.

4.1. Materials sourcing

In his thesis, Hugo Gasnier refers to the sourcing of materials as one of the "strategic steps" for earthen construction (Gasnier, 2019, p. 233). This was confirmed by different interviewees. For instance, the academic considered the availability of local earth as a condition for success:

> *"One of the conditions for success was that a good quality earth was available nearby" R01 – Academic*

This underlines the importance of finding a "*good quality earth*". What *means* "*good quality earth*", must be understood in this specific project i.e. load-bearing rammed earth project which had specific constraints that will be discussed in this chapter. However, Hugo Gasnier does not mention the role of the masons, whereas, in the case study of the construction project, the masons played a central role in this step. Indeed, according to structural engineers, the choice of earthen material requires expertise for which the experience of the mason is necessary:

> *"Where the experience of the craftsman remains essential for us is in the choice of the earth" R08 – Structural engineer*
>
> *"Scouring the region looking for earthworks with excavated earth is a lot of work, which isn't necessarily very comfortable or rewarding. You have to rely on another site, where there is going to have excavation work at a given time. All of a sudden you have to go and look at the soil, decide whether or not to*

[155] https://www.vie-publique.fr/eclairage/19461-grand-paris-projet-de-developpement-dune-metropole-de-rang-mondial

take it. I think that's a pretty stressful stage. But afterwards, ***there's real expertise behind going to examine the soil to see if it's good****. I think it's also a pleasure to find a quality of soil that you're going to enjoy working with. » R08 – Structural engineer*

The academics involved in the design of the building also believed that it was the role of the mason to select and source the material:

"And the earth sourcing? – The mason must do it." R01 – Academic

In the case study, the mission of sourcing material was therefore assigned to the mason. This step was subjected to various constraints such as normative or logistical.

The earth excavated from the site – located in a former industrial area – was too polluted to be used for construction, which necessitated finding another earth for the project. This problem of polluted earth has already been highlighted by Hugo Gasnier in the context of the Grand Paris urban areas (Gasnier, 2019, p. 233) which makes it difficult to find suitable earth in urban areas (Wright and Thorpe, 2015). The mason, therefore, had to find another construction site with excavated earth, potentially suitable for the project.

Moreover, to obtain the BREEAM label for this building, a maximum distance of 30km between the excavation site and the construction site was required, which was particularly difficult to achieve in an urban area with many polluted earths. The mason found earthen material in a rural area about 30 km from the construction site. During the interview, the mason highlighted that he already knew this type of earth since he had already used it in another construction before that of this study. This knowledge appeared important for the third-party controller in the success of earth construction projects:

"[One of the key steps] is to have some knowledge of the local earth. At least the one that will be used." R02 – Third-party controller

Logistical constraints include the need for on-site earth storage which would be available when the mason is looking for supplies, as the diggers themselves have short lead times. The issue of storage has already been discussed in Chapter 4 highlighting that the context of the building, although in an urban area, was facilitating. Good coordination and collaboration between the diggers and the design

team, especially masons, is required. The deadlines are also variable during the sourcing step, because finding suitable earth depends on the opportunities, just as the deadlines for validating the selected earth are variable (see sections 4.2 and 4.3). These delays must therefore be anticipated in the design phase.

The costs relating to the supply of materials are also to be anticipated, while unforeseen costs are considered as a barrier in the literature (Ben-Alon et al., 2020a), in particular by the clients, as highlighted by the structural engineer:

> *"But that means you have to have a contractor to fetch the earth, and the project owner or public contracting authority has to be prepared to incur costs and take steps without being sure that, at the time of the consultation for tender files, it will be successful in terms of price." R08 – Structural engineer*

However, the structural engineer also highlighted that these costs should be put into perspective because the earth is free in itself and therefore only the transport and the mission granted to the mason who will make the supply of material will cost. Also, this could be compared to other common missions, such as geotechnical investigations. Finally, the structural engineers considered that these costs would be easily absorbed if the construction project was not too small. Explaining to the clients that sourcing materials is necessary and beneficial to the earth construction project could help to make clients more inclined to pay. Once selected by the mason (Figure 6.71), the earth and its implementation had to be validated by different stakeholders according to different steps, such as prototyping and characterizing.

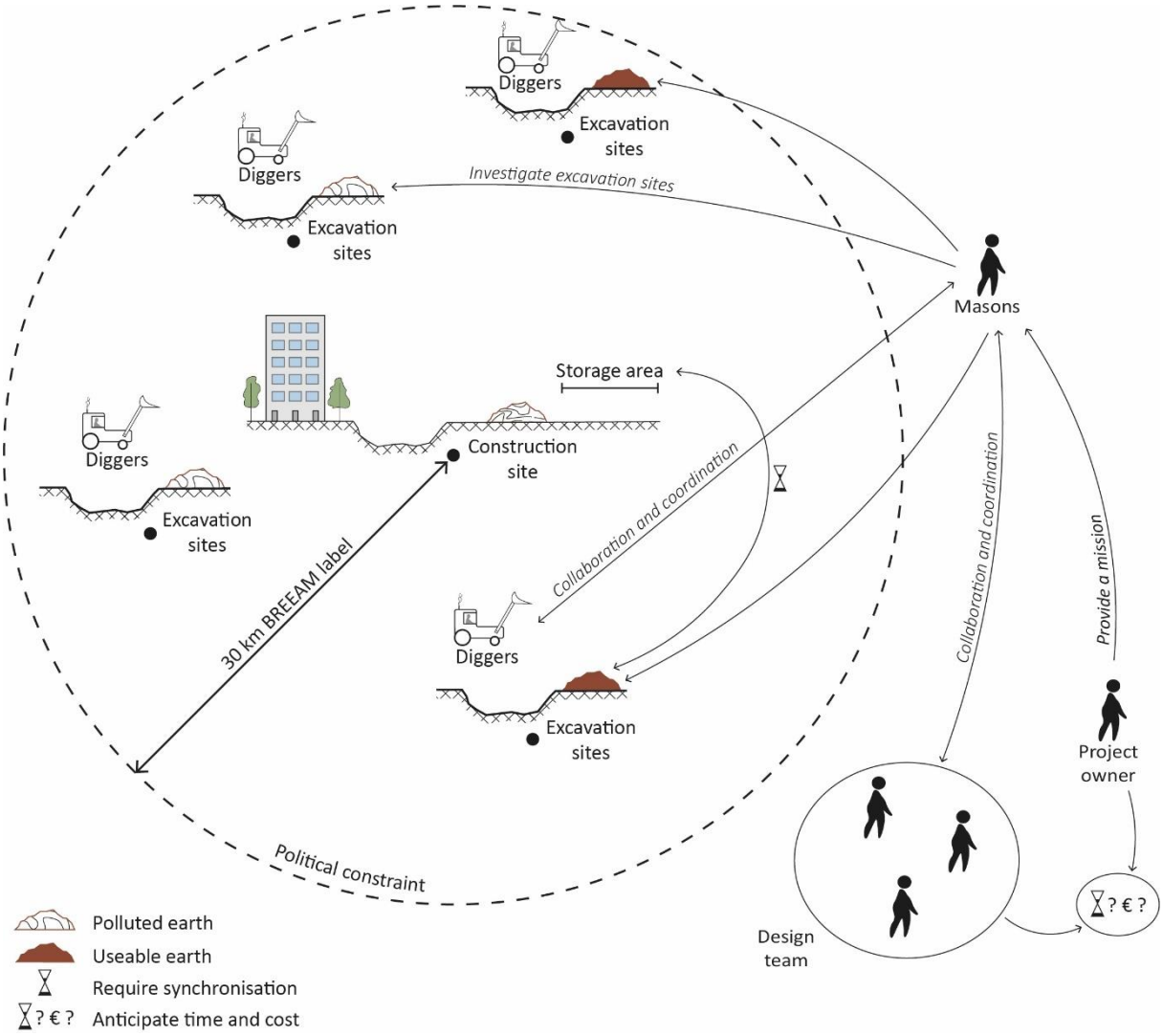

Figure 6.71: Schematic representation of the material's sourcing key step

4.2. Prototyping

Various prototypes were made during the design and construction of the building. A first prototyping session was carried out during the detailed design phase to compare the two proposed techniques at this stage of the design process: poured earth and rammed earth. Small wall prototypes of rammed earth and poured earth were manufactured to help the project owners make their choice between those techniques. However, the masons were not involved in the fabrication of the prototypes which were prepared by Academics B who were involved during this phase. Moreover, they were not prepared with the earth used for the construction.

Once the masons were involved in the project, they made new prototypes, during the technical design phase. With two different types of earth, they built three small walls with an implementation process similar to that of construction. This helped the architects to validate the aesthetics of the different earth and some technical details as the chamfers.

Finally, as requested by different stakeholders, including the urban developer, the architects, but also the masons, a prototype of the keystone was manufactured at the start of the production blocks (Figure 6.72). The architects explained that the urban developer was requesting prototyping for each construction project in the urban area. This was a way to *validate* the keystone for all stakeholders, including the masons:

> *"Some prototypes were made and [name of one of the masons] also wanted to see how the keystone would work." R07 – Architect*

As explained by the architect, prototyping was considered a key step because it helps to validate the different technical choices, and possibly adjust some of them, before launching large-scale construction:

> *"This really allows us to **validate the choices we made during the studies** before moving on to a larger scale. We can even make adjustments because sometimes we can also adjust the colours, a finish, make several proposals... So yes, for us it's a necessary step now." R07 – Architect*

These prototypes are also considered a trusted tool by some stakeholders, such as academics, who would have liked to see the prototypes at the start of the project:

> *"Do you think that prototypes should be shown beforehand?*
>
> *R01 - Academic*
>
> *Yes, maybe that would have given more confidence."*

Prototyping was, therefore, a key step in the validation of the technical earth implementation (Figure 6.73). Another key step in validation was the characterization of the material.



Figure 6.72: Picture of the prototype of keystone (source: author)

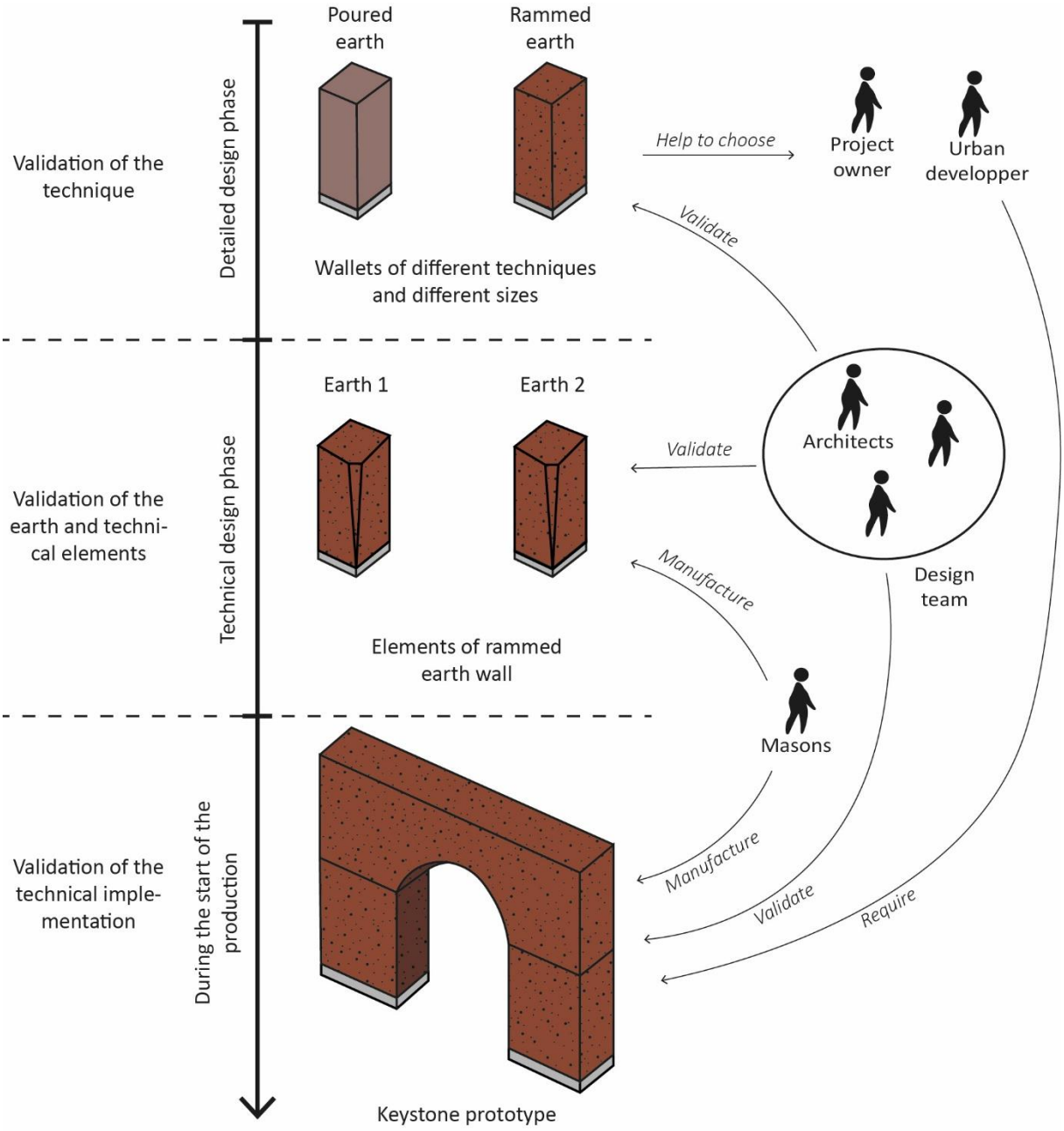

Figure 6.73: Schematic representation of the prototyping of the project

4.3. Characterizations

Different criteria can be considered for the characterization of the material. Hugo Gasnier differentiates between two types of characterization: the one of the raw resource (for example proctor tests, MBV values, Atterberg's limit, …) and the one of the implemented material to obtain some of its characteristics, such as the compressive strength (Gasnier, 2019, p. 235). However, in the project, with the design process adopted, the usefulness of the characterization of the raw resource was very limited, while the characterization of the *performance* of the rammed earth implemented was major. This is consistent with what the good practices guide proposes:

> *"It is, therefore, necessary to characterize not the raw material, but the component of the work."*[156] *("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 15)*

Besides, the characterization proposed by Gasnier (2019) is only laboratory (and engineering, i.e. based on quantified measurements and calculations) characterizations, however, one should be aware that masons also characterize the material (sometimes with sensitive tests). First to test the suitability of the earth (during the materials sourcing in particular) then to test the implementation. There is an ongoing PhD thesis on the identification of criteria for the characterization of the suitability of earth-building techniques to available earth (Verron, ongoing), where the doctoral researcher works with masons to understand and implement their criteria in cartographic databases (Verron et al., 2022). In doing so, those maps could help to indicate which earthen building techniques have the best potentials to be developed locally. According to this doctoral researcher, due to the infinite variability of earth parameters, building techniques and architectural contexts, not simple prevision tool can predict accurately earth potential for earth building: only the masons in the building context can verify earth suitability.

4.3.1. On-site characterization by the masons

As recommended by the good practice guide, the masons manufactured test walls in the same condition as the construction. Moreover, as denoted earlier, the masons had the chance to work with a similar earth (from the same earthwork site) on another construction project.

In addition, various testing was carried out during the construction phase by the masons, including shrinkage tests and compressive strength tests on full-scale specimens (about 1mx1.50mx50cm) with a press manufactured specifically for this project, along with sensitive tests (for instance to assess the water content). the compressive strength tests were produced in collaboration with the structural engineers involved in the project.

4.3.2. Characterization in laboratories[157]

Different characterizations were considered and performed in laboratories for the project, in particular the characterization of the compressive strength and hygrothermal properties of the material. Indeed,

[156] Translated from French to English by the author. Original version: « Il convient donc de caractériser non pas la matière première, mais l'élément d'ouvrage »

[157] This section describes various characterizations that have been carried out during and for the project. Only a part of this characterization has been performed by the author. Concerning the compressive strength characterization, details are provided in Chapter 1. Besides some of the hygrothermal characterizations have also been carried by the author but were not described in the manuscript as it was not the topic of study.

these are considered the most important characterizations by the academic, in the context of the studied project:

> *"For me, the really important tests were compressive strength, because that's the most important parameter we needed. [...] And the study of the drying of the walls, to get an idea of when the rammed blocks can be stacked, how long the blocks need to be left to dry... And when the building should be delivered." R01 – Academic*

Indeed, since the building has been optimised in terms of loads (during the construction process and for the in-use phase), and the structural engineers have chosen the *dry* compressive strength to design the building (see section 3), following the drying process and the evolution of compressive strength was necessary.

Then, according to the structural engineers of the project, the characterization helped to reassure the client and mostly the control officer. The design team had to provide specific justifications for the building design and the use of earthen material. Characterization and laboratory testing were one way to meet this need. However, for various reasons, this was not always possible. Indeed, some laboratory procedures were missing, for example, the assessment of rammed earth shrinkage. Another example is the justification of fire resistance. Since no official report existed on fire resistance, even though the design team believed that fire resistance was not an issue for rammed earth, certified laboratory testing would have been required, which is costly and was not planned and therefore out of budget. To avoid this problem, the design team and clients decided to modify the programmatic typology of the building by restricting access to the flat roof, to reduce the fire resistance requirements. Finally, the need for certain laboratory test procedures was discussed between the control officers and the design team (including the researchers), such as the procedure for assessing the mechanical behaviour of the joints between rammed earth blocks. While the control officers requested it to be characterised, the design team considered that such characterization was unnecessary given the size of the block.

This is important as some stakeholders consider the need to optimize the number of tests to reduce costs and time:

> *"Finally, **to use a new material, you need to be able to use it with as few tests as possible to reduce costs and lead times**. That's the heart of the*

> *matter. We could imagine, for certain processes, perhaps not earth, having such a detailed knowledge of the process that with a few measurement points during the process or afterwards, we could have a high level of confidence in the performance of the process." R05 – Standards organization employee*

This was also highlighted in Hugo Gasnier's PhD thesis by recalling the need to specify in advance the values that need to be tested:

> *"As this type of testing is practically infinite and, in some cases, very costly, it is necessary to define the characteristics to be studied by identifying the stresses (acoustic, mechanical, abrasion, humidity, etc.)."*[158] *(Gasnier, 2019, p. 235)*

This shows the need for a clear agreement on the rammed earth characterisation protocol, depending on the type of building, stated before the design phase to avoid any unanticipated additional cost. Furthermore, an optimisation of this protocol could be the topic of further research. Two types of characterizations were therefore particularly useful for the project: the compressive strength characterization (to establish the design compressive strength) and the hygrothermal characterization (to follow the evolution of compressive strength during the construction).

4.3.2.1. Compressive strength characterization

The characterization of the compressive strength was done in two steps: (1) the selection of the most efficient rammed earth concerning the constraints of the project, and (2) defining the design compressive strength using the *design by testing* method described in Section 3.

The first compressive strength assessments were then carried out just before the start of construction. Two types of earth were tested, previously preselected by the masons, with different water contents: manufacturing water content and water content after the drying process. Indeed, the sensitivity of compressive strength to the water content has already been demonstrated by many authors (Bui et al., 2014b; Champiré et al., 2016). These tests were carried out on small specimens (cylinders 15 cm in diameter and 30 cm in height).

Once selected, other compressive strength tests were performed to better characterize the chosen earth. Indeed, tests were carried out on large specimens (prisms of 30 cmx30 cm section and 60 cm height), and at various water contents, and were performed as part of the objective of obtaining an

[158] Translated from French to English by the author. Original version: "*Ce type d'essais étant pratiquement infini et très coûteux pour certains, il est nécessaire de définir les caractéristiques à étudier en identifiant les sollicitations (acoustiques, mécanique, abrasion, humidité...).*"

ATEx for the project (see Chapters 4 and 5). Testing larger specimens had the advantage of being more representative of the construction site as recommended in the Eurocode:

> *"The conditions during the tests should as far as possible be representative of those which can be expected to arise in practice." (Gulvanessian, 1997, p. 70).*

The selection of earth through compression test was a timely constraint as it depended on the material's sourcing described in the previous section. Besides, in the case of the large specimens (200 kg wall element), their size made it difficult to accelerate drying (using an oven as was the case for small specimens), so their test time was conditioned by their drying, as illustrated by the academic:

> *"Because the problem is that between the time the earth is chosen and the time you test it, it inevitably takes 2 months." R01 – Academic*

During the project, masons fabricated most of the laboratory specimens. Although this is interesting to increase the representativeness, it also raised some challenges, including the need for good coordination and collaboration between masons and laboratories in terms of logistics but also in terms of data. In particular, to analyse laboratory tests, the manufacturing water content of the specimens and the reference manufacturing water content on-site were required. To do this, while the masons were making their test wall, bags of earth were taken from waterproof bags (Figure 6.74) to be tested in the laboratory by weighing (details on how the water content is assessed in laboratories are provided in Chapter 1). Besides, specimens of the wall were taken to measure the dry density by hydrostatic weighing. Concerning the manufacturing water content, difficulties have arisen in its definition, in particular, due to the lack of suitable protocol for earth containing large grains (between 2 cm and 5 cm in diameter). These two parameters (manufacturing water content and mean dry density) were also useful in the quality control established for the project which will be described in the next section.



Figure 6.74: Picture, extracted from the test report showing the different specimens collected. On the top, 14 specimens of the wall for dry densities measuring. On the bottom, 6 earth bags for water content measuring

Finally, it should be noted that the full characterization of the compressive strength took place after the design phase, which meant that the structural designers had to anticipate the probable value that would be obtained. Characterization was then more a matter of verifying the performance of the material used. However, some stakeholders, in particular the academic interviewed, believe that basing the design on the performance of the material and therefore characterizing the material first would be preferable, even if it is different from what is commonly done in mainstream construction:

> *"**you have to choose the soil before and then you design. Concrete is different. You design and then, depending on the constraints you have, you can choose the appropriate concrete**. […] That means that you start with the material and then you have to adapt your architecture and design to your material. So, you go the other way around." R01 – Academic*

This section underlined the usefulness of testing small specimens instead of big ones, the latter representing a time constraint due to drying. Therefore, it shows that Chapter 1 answers a practical question by proposing a method of scaling-down specimens that would therefore speed up the process of characterizing the compressive strength. The principle of this method, as described in Chapter 1, is to sieve the earth to manufacture homogeneous specimens based on equivalent[159] parameters

[159] Based on the similitude relation

(manufacturing water content and dry density), calculated from on-site ones. This means that the masons should have already been involved in the project at the time of characterization and had already selected the earth and made their own characterization and prototype so the on-site parameters could be assessed (see Figure 1.26). If the design is based on this characterization (following the design-by-testing procedure), therefore, this would require the mason to be involved early in the design, which would have consequences on the current construction process where masons are generally only called in during the construction phase. SFigure 6.75 proposes a schematic representation of the characterization steps that have been achieved during the process of the case study (in black colour). The method developed in Chapter 1 to answer objective 1 is highlighted in brown colour in that process and represents an optimisation of the part of the process framed in dotted brown. Indeed, using this method to manufacture the samples, based on on-site parameters would allow us to avoid manufacturing big prisms that are cost and time-intensive to test. Besides, by using this method, the specimens could be manufactured in laboratories for greater repeatability but still keeping the representativity of the on-site.

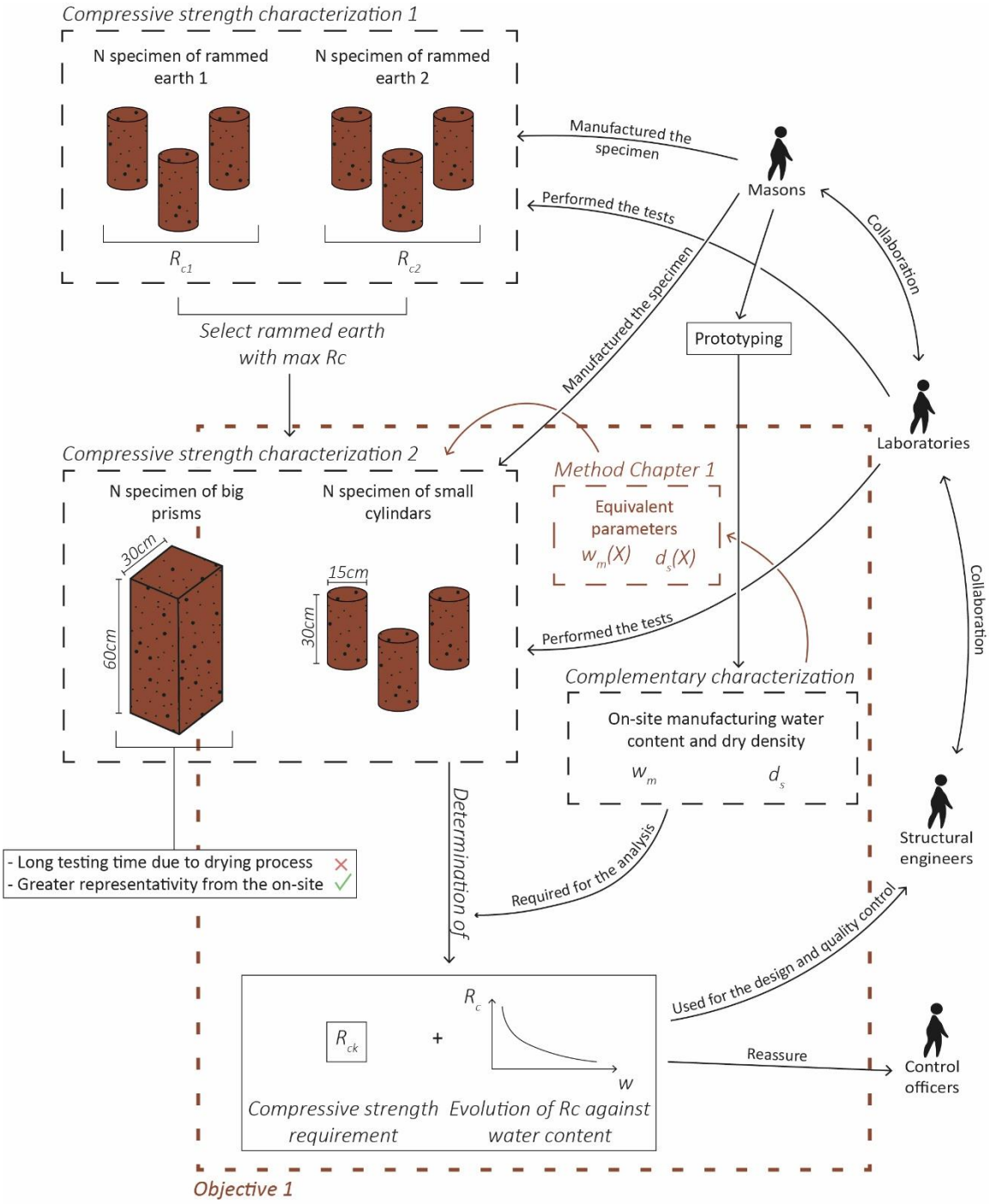

Figure 6.75: Schematic representation of the characterization key steps with a focus on the mechanical characterization

4.3.2.2. Hygrothermal characterization[160]

To complete the characterization of the compressive strength, a hygrothermal characterization was also carried out. This was useful to assess the drying time of the walls in order to follow the increase of their compressive strength while drying, during the construction work. Indeed, as explained in

[160] The hygrothermal characterization has not been detailed here as it was out of scope of the thesis. However, the reader can refer to the article of Losini et. al (2023) where details are provided on this characterization. Besides, a current thesis (Théo Poupard) is going on the topic of hygrothermal behaviour using data carried from building's case study, started in 2022.

Section 3, the structural engineers controlled the drying of the rammed earth blocks to check, regarding the loads applied during construction (inferior to the load for the finished building), whether it was possible to continue stacking the walls. This was done in collaboration between masons, structural engineers and academics. In addition, the drying was also measured on-site by the masons as they constructed test walls for each row of blocks which were weighed at different times.

Finally, the evaluation of the drying time was important. Indeed, control officers asked to verify that the rammed earth of the façades had reached the water content corresponding to the compressive strength used for the design, before the delivery of the building.

4.4. Prefabrication

Another key success factor of the project was the on-site prefabrication of rammed earth blocks. Prefabrication is sometimes considered in the literature as allowing to overcome the dependence on the climate conditions of the rammed earth production (Zawistowski et al., 2020). However, it is off-site prefabrication to which it is generally referred, which could increase environmental impact in the case of transportation (A. Ventura et al., 2022). In the case study, the blocks were prefabricated using a machine (transportable on a truck) designed by the masons themselves, initially to reduce the hardship. This is similar to the principle of a *flying factory,* found in the literature (MacDougall, 2008), where the machine is transported from site to site to locate production on or near the construction site. If prefabrication was considered from the competition phase, it is however the masons that brought their specific means to prefabrication. This process was considered a condition of success by most stakeholders to build the arches:

> *"It's an extremely interesting system... In any case, we couldn't have done the arches any other way." R04 – control officer*

It was also preferred to other prefabrication methods such as those that favour a fixed factory:

> *"**We had the right people, with the right methodology, because they had their flying factory on the construction site**. So that saves a workshop that [name of another rammed earth producer] rents somewhere to make the blocks, then transports them, which creates costs, not to mention a carbon footprint. So effectively, I think that with on-site prefabrication, we were also on the right solution." R07 – Architect*

And indeed, the prefabrication process had many advantages. First, it may overcome the issue of "continuous setting-up, aligning and stripping of formworks" which is considered by some authors as time-consuming for rammed earth construction (Gallipoli et al., 2017). Then, it offered flexibility in the organisation of the construction compared to traditional rammed earth fabrication with the possibility to fabricate on rainy days and the ability to fabricate some of the blocks before construction begins so they can dry out and increase their compressive strength, as well as shrink. In fact, in this project, as already detailed in Chapter 4, the most loaded blocks (the bases of the arches and the keystones) were prefabricated around 9 months before being assembled (Figure 6.76).

> *"And also, to organise the construction site. Because it enabled us to build blocks over two seasons. To pre-dry the blocks that are most loaded [...]. So that really enabled us to organise the whole site and coordinate all the work involved. That's for sure." R07 – Architect*

The prefabrication of the blocks also facilitated the control of quality, as detailed in the next section, and explained by the structural engineer:

> *"It's better controlled. It allows this control by weighing which is impossible on traditional rammed earth." R08 – Structural engineer*

Finally, the machine used for the prefabrication was described by three stakeholders as offering greater quality and repeatability of the rammed earth, with greater homogeneity of the blocks, reducing the potential dispersion of their mechanical characteristics.

> *"Compaction was managed automatically by a machine,* ***which ensured a good repeatability of the blocks****." R01 – Academic*

> *"The fact that the blocks were manufactured by a machine meant that* ***all the blocks had constant compaction, which meant constant humidity levels and constant strength at the time of manufacture****." R03 – Project owner*

"Especially as with the [Name of the mason] machine, we're no longer in the same situation as before, with random damage where the strength of the player plays a role. ***We really have a machine that always hits with the same force, with layers that are always the same thickness, so impeccable regularity****." R07 – Architect*

The repetitiveness of the production was a way of reassuring the control officers:

"Instinctively, I have the impression that how [name of the mason] has constructed this building is more reassuring." R04 – Control officer

"it reassured them that it was actually done by a machine because we trust machines more than we trust people" R01 – Academic

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Figure 6.77 provides a schematic representation summarizing the results obtained in this section.



Figure 6.76: Picture of premanufactured blocks (source: author)

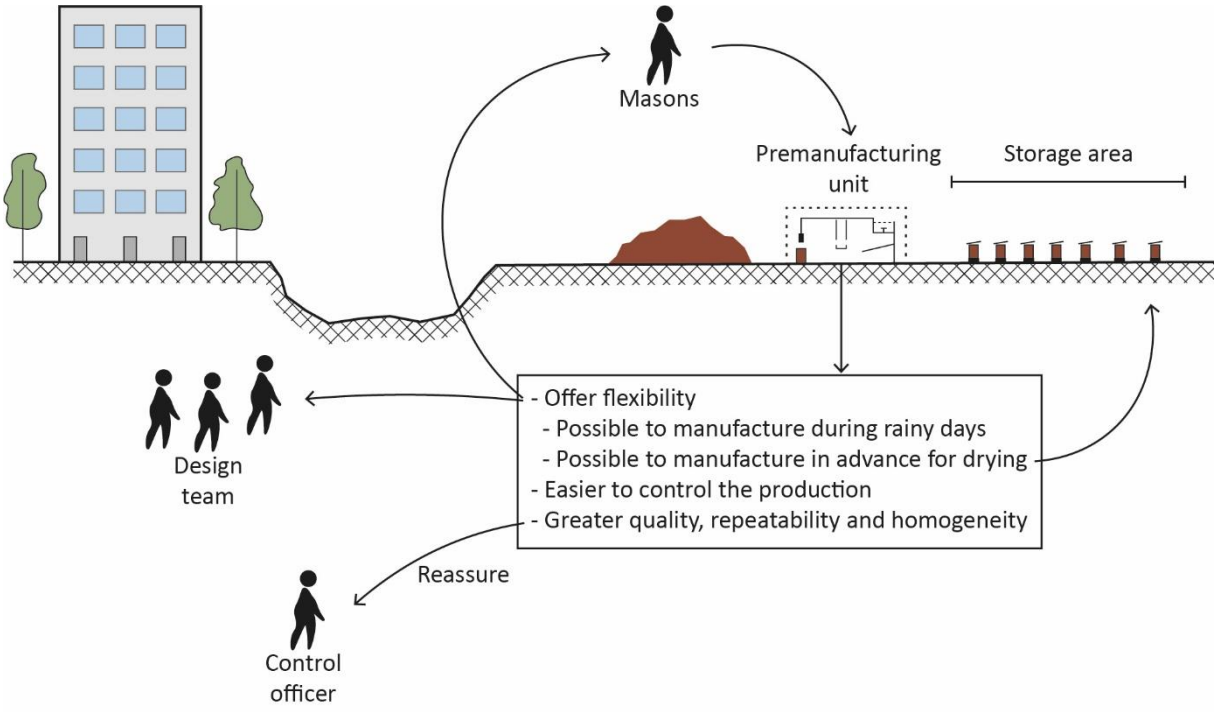

Figure 6.77: schematic representation of the prefabrication key step

4.5. Quality control

Finally, quality control is the last key step of the performance approach adopted for the design and construction of the project. Indeed, the performance approach requires *verifying* and *demonstrating* "that a particular material or building solution [rammed earth façades in our case] will meet a given performance criteria" (Foliente, 2000). Two different quality controls can be considered in the adopted approach: one related to the verification of the criteria of resistance to compression (control of the production and assembly); one related to the verification of the behaviour of the building after delivery (control of the relative humidity inside the walls, control of creep and inspection contract).

These quality controls are higher than the controls in mainstream construction highlighting high standards when it comes to the rammed earth in this project, as highlighted by various interviewees:

"Quality control was certainly better than the one carried out on poured concrete on the building site." R01 – Academic

"The project was very, very, very closely supervised. The manufacture of each block was monitored and documented, and nothing was left to chance. » R07 – Architect

"in their market, they [the masons] had to deliver a tighter control" R08 – Structural engineer

Besides these technical engineered controls, the masons carried out self-checking of production as recommended in the good practices guide, in particular checking the water content during the fabrication, the height of the layers before compaction and the quality of the compaction ("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 16).

Two quality control can be described including the verification of the compressive strength criteria and the verification of the building's behaviour.

4.5.1. Verification of the compressive strength criteria

4.5.1.1. Production control

The strengthening of production control was necessary for different reasons. First, Eurocode 6 for masonry structures establishes the choice of the safety factor applied to the compressive strength according to the level of quality control. Indeed, as already explained in section 3.3, the safety factor was low compared to usual:

"We opted for the smallest safety coefficient, but in return, we had to introduce tighter controls." R08 – Structural engineer

Besides, this production control was also necessary for the risk assessment relative to rammed earth and to reassure the control officers accordingly. Thus, it was required for the insurability of the building[161]. Indeed, most of the technical engineered[162] quality controls were put in place after the refusal of the ATEx process at the request of the control officers.

"I think that quality control is useful for, at some point, I think you have to meet the expectations of our zero-risk society and be insured." R08 – Structural engineer

[161] The link between control officers and insurability have been described in chapter 4.

[162] "engineered" is notified to make visible the fact that masons also control the quality of their production, but not necessarily in an engineered way (i.e. quantified based on equations).

A specific approach has, therefore, been developed to control the production of the blocks and in particular to verify the concordance with the compressive strength requirement. Some indirect on-site compressive strength measurement methods have recently been studied in the literature, notably through the use of non-destructive testing using rebound index and ultrasonic pulse velocity (Martín-del-Rio et al., 2020). However, it must be noted that the number of publications is very limited on this topic. In the case of the building, it was chosen to verify indirectly the compressive strength both by calculating the dry densities of each block (1), and following the evolution of compressive strength against water content (2). Therefore, the requirement of a minimum compressive strength has become a requirement for a minimum dry density (defined as 1900 kg/m^3 in the project), as the two are known to be tightly correlated[163]. The calculation of the dry density was carried out by measuring, the weight, volume and water content of each block during the fabrication. The latter began to be measured after the ATEx refusal so after the first production of blocks. This process was explained by the interviewed structural engineer:

> *"What were the strategic points of quality control: it was to **guarantee that we had minimum strength**. As strength is linked to compactness, we had to **ensure that we achieved a level of compaction that gave the rammed earth a sufficient minimum densit**y. And **this density is a dry density, so if we don't know the water content during manufacture, we can't determine the dry density of the rammed earth at the time of manufacture**." R08 – Structural engineer*

By this process, the dry density of each block was assessed and if it was lower than the targeted dry density, previously defined in concordance with the characterization of the compressive strength, the blocks were destroyed. Nevertheless, the masons highlighted that this only happened a few times. Besides, another aim of the control of the fabrication water content was also to guarantee the consistency of the production process:

[163] The higher is the dry density, the higher is the compressive strength for a given earth, see Chapter 1

> *"And the other aspect [...] was also to guarantee consistency and regularity of water content in the production process, to ensure that it was a truly repeatable process." R08 – Structural engineer*

To control the measurements that were made by the masons, a third party was involved in the project. This mission was unusual, as highlighted by the person involved in this third-party control:

> *"That's a specific job, very unusual. [...] I've been a control officer for 20 years, and this is the only one I've ever done." R02 – Third-party controller*

This third-party control was required by the control officer after the refusal of ATEx (see appendix D). The mission was provided to a control officer from a different office than the one already involved in the project, which might have reassured the control officer:

> *"[the mason] put the idea of working with me to the control officer, who was also reassured to have a control officer opposite. Among control officers, we know what we want. And at [name of the control office], we have a good reputation, especially for these materials, where we're quite pioneering." R02 – Third-party controller*

Finally, all these procedures created tensions between masons and control officers. While the control officer asked an objectification by the analysis of engineering data of the fabrication process, the masons were sceptical, frightened by a potential appropriation of their knowledge by the engineers. Besides, according to the structural engineer interviewed, the control officers lacked trust in the masons when the latter felt pressured by this permanent control. Especially since the masons were not used to such procedures, which they sometimes considered unnecessary, in particular for the measurements of the fabrication water content, as explained by the structural engineer:

> *"**[the mason]'d never done it before and went to great lengths to do it**, because of the water content, the craftsman can feel it. The consistency of the earth will change very quickly to within 1 % water content. So, they can*

say if the water content isn't more or less constant. So, it was really just a formality for outsiders who didn't trust the artisans." R08 – Structural engineer

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However, the masons agreed to adhere to this approach, in particular, because of the relationship of trust with the structural engineers, but also to demonstrate the quality of their work.

"The mason trusted us, and they didn't want to do anything stupid either. They wanted to show that artisans can do as well as the industry. That we could build substantial buildings out of rammed earth. They had confidence in us and we worked very, very hard to put together their files and their studies, so that was what he owed us." R08 – Structural engineer

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Therefore, this production control relied once again on the trust relation and collaboration between, in particular, masons and structural engineers.

4.5.1.2. Drying control

Additionally, as the elevations of the walls were conditioned on the correct drying of the blocks to ensure sufficient compressive strength, the drying was also controlled.

"We are also interested in the dynamics of the initial drying phase, during the construction phase, for scheduling purposes. Because drying takes a very long time and can, at some point, slow down the stacking of the walls" R08 – Structural engineers

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This was verified both by monitoring the mass loss of the test blocks made by the masons and by calculations based on the characterization described in section 4.3.

4.5.2. Verification of the building's behaviour

Finally, after the delivery of the building, various verifications of the behaviour of the building were required by the control officers: monitoring the hygrothermal behaviour; creep monitoring; and monitoring of the rammed earth through an inspection contract established with the masons.

4.5.2.1. Hygrothermal behaviour monitoring

The monitoring of the hygrothermal behaviour was the responsibility of the thermal engineering office which had to monitor the rammed earth façade with hygrothermal probes to measure the relative humidity inside the walls. Indeed, relative humidity is correlated to the water content of the walls (Chabriac et al., 2014). Therefore, the control officers required its measurement to ensure that the water content during the service life would not exceed that corresponding to the water content of the compressive strength tests (about 1%). The relative humidity was therefore monitored by the thermal engineers, for two years after delivery.

> *"So, we installed probes to check the drying of the raw earth, which was satisfactory." R04 – Control officer*

> *"They [control officers] asked us to monitor the rammed earth core to check that the moisture content remained within the range calculated for the safety of the structure." R06 – Thermal engineer*

In addition, the thermal engineers also had to monitor the thermal environment and energy consumption, as required by the urban planner. Indeed, it was a condition from the urban planners to exempt this building from respecting the thermal regulations and labels as described in Chapter 5.

> *"They [Urban planners] told us "OK for the derogation, but we want to understand what's going on in this building. We want you to provide us with monitoring of comfort and consumption in the building for 2 years after construction." R06 – Thermal engineer*

4.5.2.2. Creep monitoring

The lack of scientific evidence of the absence of creep of the rammed earth façades was one of the reasons for the refusal of the ATEx by the commission, which is an illustration of the lack of scientific evidence that is sometimes considered a barrier in the literature (Mohammad Sharif Zami, 2021). Although structural engineers did not consider creep as a building design issue, this issue continued to create debates with control officers after the ATEx refusal:

> *R04 – control officer:*

"When we [control officers] decided to ignore the rejection of the ATEx, these things continued to be at the centre of the debate."

Interviewer:

"What do you have in mind?"

R04 – control officer:

"For example, creep! The creep of raw earth. So, [name of one of the academics] says that raw earth doesn't creep. I want to believe them. But where are the tests, where are the qualifications? Where are the scientific studies? When you make a new cement, low-carbon cement, for example, creep tests are carried out. These tests last a year!"

Thus, at the end of the construction, the control officers were asked to monitor the building with targets (Figure 6.78) allowing a surveyor to measure the potential movements of the rammed earth façades over time. The project owner interviewed explained that this surveyor was mandated to come and take measurements every three months for three years. In addition, this creep monitoring was a condition imposed by the control officer for not installing the timber posts, already described as a controversy in Chapter 5. The latter would be installed in the event of creep of the rammed earth façades, which is not yet the case:

"At the end of the project, I asked for a monitoring campaign to be carried out. So, we put targets in place so that we could check the XYZ movements of the façade. No movement was observed. This would seem to prove that there is no real creep." R04 – Control officer

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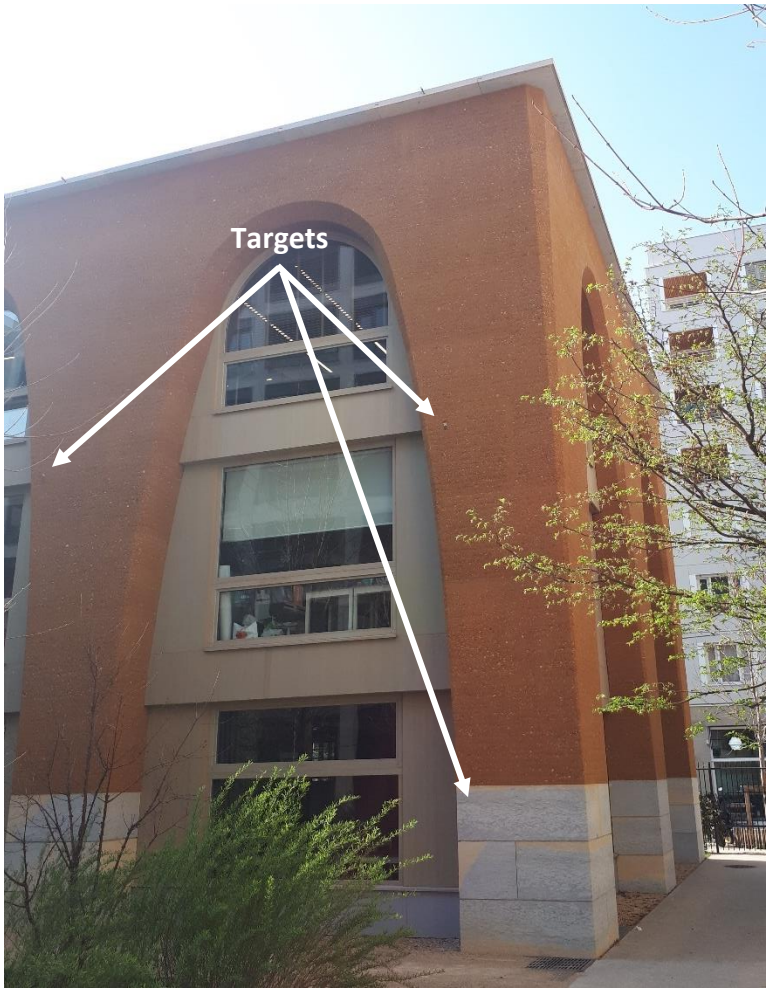


Figure 6.78: Picture of a portion of the facade highlighting some of the targets to measure the creep (source: author)

4.5.2.3. Rammed earth monitoring

Finally, to check the behaviour of the rammed earth façades and in particular, to check for any pathologies or cracks, an inspection contract has been drawn up with the masons. The masons are assigned *"a mission of regular inspection of the state of the rammed earth structure".*

The establishment of this contract was a means of overcoming the question of the maintenance of the earth, and in particular to survey the potential risk of pathologies. Indeed, there is a potential need for regular maintenance, whereas, in the French insurance system, any cracks might be considered a disorder and therefore require the intervention of the ten-year insurance. It was, therefore, important to avoid any confusion between what is pathological[164] and what is routine maintenance[165]:

[164] For which ten-years insurance could work

[165] For which masons could intervene on the maintenance of the rammed earth. In this case, a new contract should be created. The initial contract is only an inspection one to detect any pathologies or any need of maintenance.

"In the final report, we made it clear that a crack in the raw earth was not necessarily pathological, but that it had to be maintained. We tried to debate what was normal maintenance for raw earth and what was pathology." R04 – Control officer

As noted in the final report of the control officers, to facilitate any maintenance work by the masons, the control officers recommended keeping 0.1 m^3 of earth on-site for ten years, under the responsibility of the client. This type of contract might be a way to tackle the need for regular maintenance that is often cited as a barrier in the literature (Ben-Alon et al., 2020a; Danso, 2013; Foruzanmehr, 2013; Kulshreshtha et al., 2020), and could be an illustration of the consideration of cyclical maintenance of the building in the design (Moriset et al., 2021).

Figure 6.79 schematically summarizes this section. The two requirements represented are those defined in section 4.5.1.1. The first requirement corresponds to verifying the concordance in dry densities of the blocks while the second corresponds to checking the evolution of compressive strength against water content (particularly useful during the construction phase).

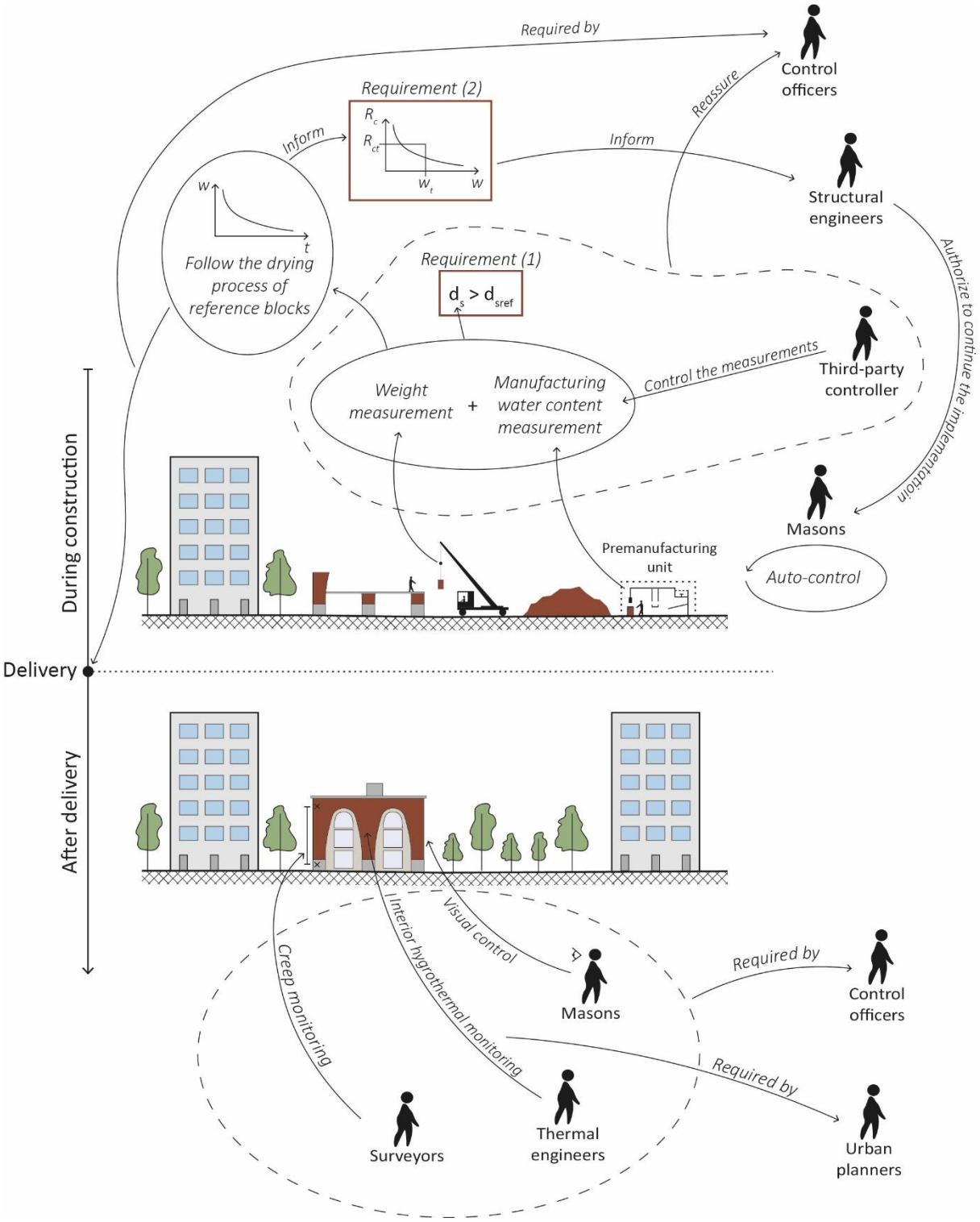


Figure 6.79: Schematic representation of quality control's key step, the condition $d_s > d_{sref}$ corresponds to the requirement on the dry density compared to the dry density reference, which is the indirect verification of compressive strength. The second requirement represents the verification of the compressive strength at time t of construction (R_{ct}) on the curve of compressive strength on water content (Chapter 1), informing the structural engineers.

4.6. Conclusion of the section

In this section, the various key steps (materials sourcing, prototyping, characterizations, prefabrication and quality control) adopted for the implementation of the design by testing performance approach,

have been described. In the context of the building and from the definition of barriers and drivers in this PhD thesis, these key steps having made it possible to produce the *load-bearing rammed earth* façades, can be considered as drivers, as they helped to achieve consensus among stakeholders of the case study. Various challenges relative to these key steps were also described. The role of the different stakeholders involved was given, highlighting the collaborative work to establish this design method, particularly within the extended design team (composed of architects, structural engineers, thermal engineers, masons and researchers), where the masons played a central role. Finally, the method of fabricating specimens proposed in Chapter 1 has been situated in this process, in particular in the characterization, which will now be discussed further.

5. Situating the mechanical issue developed in this PhD and positioning the researcher

This section will address the main aim of this thesis as described in the introduction: how to situate civil engineering scientific knowledge, in earth construction field. First, a discussion on the link between situated knowledges and the need for modesty will be provided, then, the knowledge developed in Chapter 1 (i.e. the method of fabricating scale-down specimens based on similitude relation) will be situated thanks to the results of the Chapters 4, 5 and 6. And finally, an autocritique of the published article related to Chapter 1 through a comment on the introduction will be developed, as a reflexive strategy to avoid the bias often found in literature that has been described in Chapter 2.

5.1. Being a researcher: following the need for modesty

In her chapter *Modest witness: Feminist diffractions in science studies* (Haraway, 1996), Donna Haraway questions the metaphor of the modest witness (to describe scientists) from positivist philosophy to rearrange it in her *situated knowledge* theory. She argues that, from the positivist perspective, the modest witness can observe the world without being part of it, being invisible (because modest), and therefore perfectly neutral. This has already been described in the introduction as a mistaken position, or at least something that I do not believe is possible. However, as Donna Haraway pursues her theory of situated knowledge, there is a new way to be a modest witness: to assume that we are part of the social realities and that we aim for objectivity instead of being objective. This is how situated knowledge can be understood as explained by Frasch (2020), citing Haraway (1997):

> *"**Knowledge must 'situate itself'** [...] **in the sense that it must recognise itself as the product of a complex historical trajectory** that makes it irremediably partial in both*

> *senses of the word.* ***At the heart of this alternative strategy is an imperative of 'modesty'***"[166] *(Frasch, 2020)*

Therefore, assuming and highlighting the complexity (in our case, not from a historical trajectory, but at least in interaction with the socio-political realities) of any knowledge is a way to tend toward situated research. Throughout this thesis, the study of barriers and drivers to the use of earth for construction highlighted the complexity of interactions between technical, economic, organizational, political and socio-cultural factors. Underlining this complexity was necessary to aim at situating the research developed in Chapter 1 that now will be discussed.

5.2. Situating the mechanical issue in performance approach and socio-political realities.

As explained in Chapter 1 and depicted in section 4.3.2.1., the method developed for testing small specimens answered a practical issue embedded in the case study. The group "practical issue of testing small specimens representative to the on-site and associated method" will be called φ1 in this section for a matter of clarity (see Figure 0.20, in the introduction of the thesis). As shown in this Chapter, φ1 is an integral part of a process of design based on different key steps (materials sourcing, prototyping, characterization, prefabrication, and quality control), Figure 6.80. These processes are interconnected and involve various stakeholders (architects, structural engineers, control officers, project owners, thermal engineers, masons, and academics, among others that were not depicted in this thesis), with different interests and motivations (see Chapter 5). Indeed, in the performance design approach chosen by the structural engineers, the materials sourcing, carried by the masons that first validated the earth in terms of implementation, was necessary before or simultaneously with the material characterization in order to select the appropriate earth in terms of compressive strength performances. Then or simultaneously, prototyping, by the masons, was needed to validate some technical details along with the aesthetics of the implementation validated by the design team (in particular the architects) and the project owners. Prototyping by the masons along with assessment in laboratories helped to define the on-site key parameters (on-site manufacturing water content and dry density) that were required for the analysis of the second campaign of compressive strength characterization on the previously chosen earth. In the case study, the specimens tested were made by the masons, but the method developed in Chapter 1 can be considered as an optimisation[167] of this

[166] Translated from French to English. Original version: « Les savoirs doivent « se situer » […] au sens où ils doivent se reconnaître comme les produits d'une trajectoire historique complexe qui les rend irrémédiablement partiels et partiaux. Au cœur de cette stratégie alternative se trouve donc un impératif de « modestie »

[167] Optimisation here should be understood in terms of facilitating the laboratory testing, by scaling-down the specimens. Indeed, testing small specimens compared to full-scale specimens require less sophisticated equipment (smaller press, smaller oven for drying specimens, …). Small specimens are also easier to manufacture and manipulate (drying process,

part of the process, as specimens can be fabricated in the laboratory from the key on-site parameters. This second characterization, assessing the evolution of compressive strength against the water content helped for the quality control, mainly required by the control officers. Finally, premanufacturing the blocks thanks to the machine (flying factory) developed by the masons was a necessary condition in this process, in particular, to establish the quality control protocol. The latter has been established in collaboration between control officers, structural engineers, third-party controllers, academics and masons. This constitutes the design method of the case study among which φ1 have been situated.

But this method of design can also be situated. Indeed, it has been shown in Section 3, that it was a performance-based method. In Section 2, it has been discussed that the performance approach and prescriptive approach have different advantages, disadvantages and implications for the stakeholders, in particular for the masons (i.e. socio-political implications). Particularly, the design method of the case study provided a crucial role to the masons (along with other stakeholders, such as the structural engineers). This had different implications that have been analysed in Chapter 5 (for example, financial difficulties encountered between project owners and masons, but also collaboration and knowledge exchange between the masons and the design team that helped obtain the building that is known today). Therefore, here the consequences (positive or negative according to the stakeholders[168]) are limited to the case study. However, one should be aware that if such a method becomes standardized, it would have implications for the stakeholders (for example, changing the role of the masons in the design process) and therefore implications on socio-political realities. Additionally, the design method, and the case study, were context-specific, in particular in the French normative context, where the control officers play an important role. Once assuming both the socio-political realities implication and the contextuality of φ1, it is possible to understand that other ways could have been possible: in other contexts (socio-cultural, normative, scale, …), for other earth construction techniques, or other approaches (prescriptive vs. performance), etc[169].

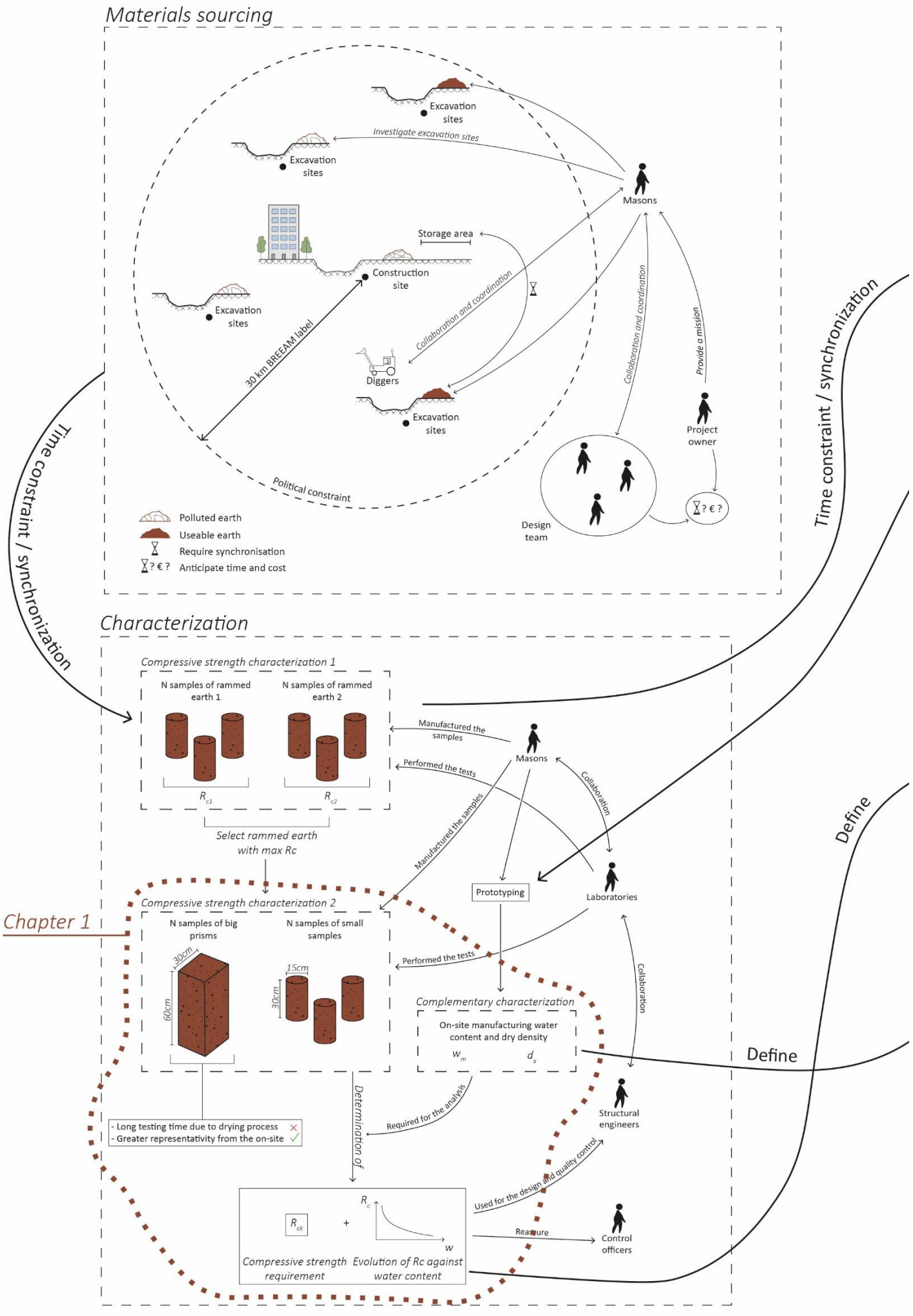
All of this process was therefore a way to situate φ1. In other words, to appreciate and, at least attempting, to make visible the complexity in which this knowledge has been produced. This underlines that φ1 was only a partial perspective as defined by Donna Haraway.

moving specimens, …). This could allow either to reduce costs by reducing the number of specimens or increasing the number of specimens tested to obtain better statistical representation of the results.

[168] Let us remind that the purpose of this thesis is not analyse these consequences but to try to be as transparent as possible.

[169] Here the aim is just to point out that the problem φ1 is situated in itself. However, investigating the different possibilities was not into the scope of the study. What is major though, following situated knowledges theory, is to explicit as much as possible the situation of the study in order to allow reflecting on the interactions between the values of the researcher (or the reader) and the research carried on.

Now that we are aware of this, it is interesting to revisit the introduction of the first article published, related to φ1, to critique it.


Materials sourcing
Excavation sites
Investigate excavation sites
Excavation sites
Masons
Storage area
Construction site
Excavation sites
30 km BREEAM label
Collaboration and coordination
Diggers
Excavation sites
Collaboration and coordination
Provide a mission
Project owner
Political constraint
Design team
? € ?
Polluted earth
Useable earth
Require synchronisation
? € ? Anticipate time and cost
Time constraint / synchronization
Time constraint / synchronization
Characterization
Compressive strength characterization 1
N samples of rammed earth 1
N samples of rammed earth 2
R_{c1}
R_{c2}
Select rammed earth with max Rc
Manufactured the samples
Masons
Performed the tests
Collaboration
Manufactured the samples
Prototyping
Laboratories
Compressive strength characterization 2
N samples of big prisms
N samples of small samples
30cm
60cm
15cm
30cm
Performed the tests
Collaboration
Complementary characterization
On-site manufacturing water content and dry density
w_m
d_s
Define
Structural engineers
- Long testing time due to drying process
- Greater representativity from the on-site
Required for the analysis
Determination of
Used for the design and quality control
R_{ck}
+
R_c
w
Compressive strength requirement
Evolution of Rc against water content
Measure
Control officers
Define
Chapter 1

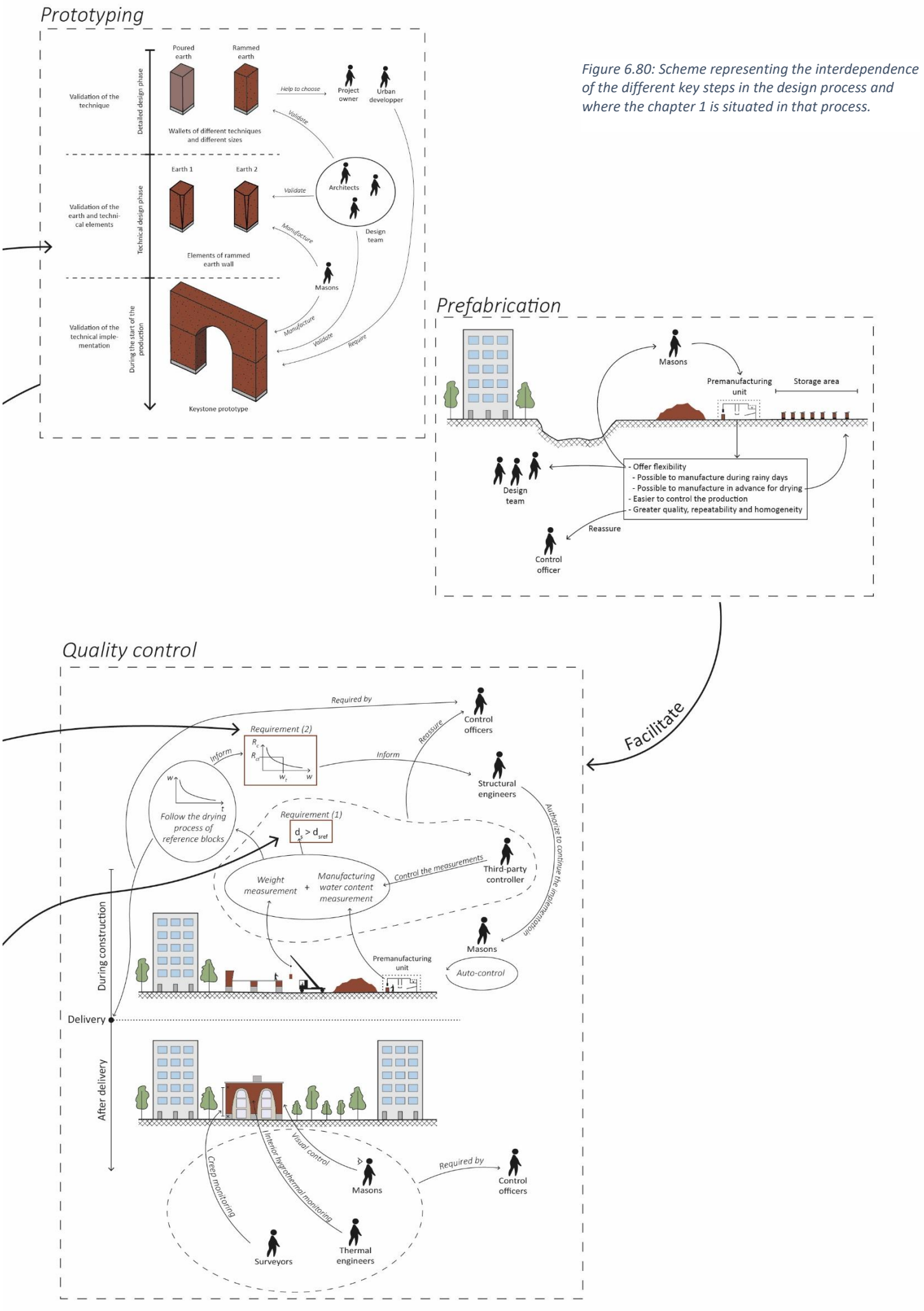
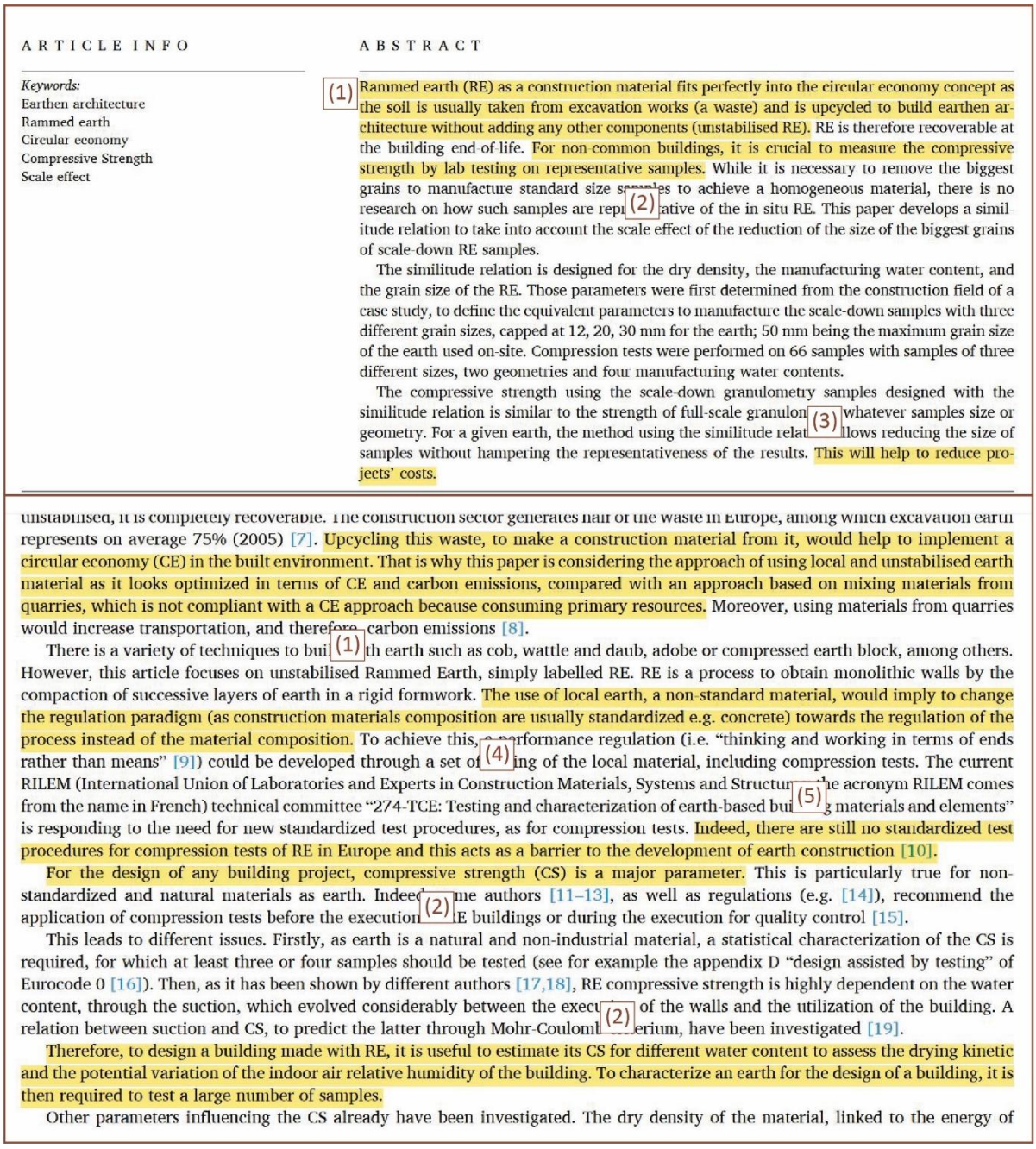


Figure 6.80: Scheme representing the interdependence of the different key steps in the design process and where the chapter 1 is situated in that process.

5.3. An autocritique: discussing the article's introduction

In an approach of reflexivity, which is consistent with situated knowledges theories, it is interesting to establish an autocritique of the first article I[170] published as a first author, namely (Pelé-Peltier et al., 2022a). Indeed, Chapter 2 highlighted that the introduction of articles often hides lack of situating by using barriers without scientific references to support it. Additionally, it has been shown in Chapter 2 that how barriers are often investigated can lack of situating in itself. Finally, as introductions aims to *situate* (consciously or not, and properly or not) research questions it is interesting to focus on it. Therefore, considering the reflection adopted in this thesis, I will comment the introduction of the article previously cited, based on extracts (Figure 6.81).

[170] It is known that, for civil engineering thesis and more generally engineering studies, it is uncommon to use the first-person singular. However, it is commonly used in research using situated knowledges theory. Indeed, as the purpose of such research is to reflect on the interactions between the values carried by the researcher and the research itself, the researcher becomes an object of study. Therefore, to be transparent on this reflexivity, it makes sense to use the first-person singular that have been chosen for this section.



ARTICLE INFO

Keywords:
Earthen architecture
Rammed earth
Circular economy
Compressive Strength
Scale effect

ABSTRACT

(1) Rammed earth (RE) as a construction material fits perfectly into the circular economy concept as the soil is usually taken from excavation works (a waste) and is upcycled to build earthen architecture without adding any other components (unstabilised RE). RE is therefore recoverable at the building end-of-life. For non-common buildings, it is crucial to measure the compressive strength by lab testing on representative samples. While it is necessary to remove the biggest grains to manufacture standard size s[illegible]es to achieve a homogeneous material, there is no research on how such samples are repr(2)ative of the in situ RE. This paper develops a similitude relation to take into account the scale effect of the reduction of the size of the biggest grains of scale-down RE samples.

The similitude relation is designed for the dry density, the manufacturing water content, and the grain size of the RE. Those parameters were first determined from the construction field of a case study, to define the equivalent parameters to manufacture the scale-down samples with three different grain sizes, capped at 12, 20, 30 mm for the earth; 50 mm being the maximum grain size of the earth used on-site. Compression tests were performed on 66 samples with samples of three different sizes, two geometries and four manufacturing water contents.

The compressive strength using the scale-down granulometry samples designed with the similitude relation is similar to the strength of full-scale granulon(3)whatever samples size or geometry. For a given earth, the method using the similitude relat[illegible]llows reducing the size of samples without hampering the representativeness of the results. This will help to reduce projects' costs.

unstabilised, it is completely recoverable. The construction sector generates half of the waste in Europe, among which excavation earth represents on average 75% (2005) [7]. Upcycling this waste, to make a construction material from it, would help to implement a circular economy (CE) in the built environment. That is why this paper is considering the approach of using local and unstabilised earth material as it looks optimized in terms of CE and carbon emissions, compared with an approach based on mixing materials from quarries, which is not compliant with a CE approach because consuming primary resources. Moreover, using materials from quarries would increase transportation, and therefore carbon emissions [8].

There is a variety of techniques to bui(1)th earth such as cob, wattle and daub, adobe or compressed earth block, among others. However, this article focuses on unstabilised Rammed Earth, simply labelled RE. RE is a process to obtain monolithic walls by the compaction of successive layers of earth in a rigid formwork. The use of local earth, a non-standard material, would imply to change the regulation paradigm (as construction materials composition are usually standardized e.g. concrete) towards the regulation of the process instead of the material composition. To achieve this, a performance regulation (i.e. "thinking and working in terms of ends rather than means" [9]) could be developed through a set of(4)ing of the local material, including compression tests. The current RILEM (International Union of Laboratories and Experts in Construction Materials, Systems and Structur[illegible]e acronym RILEM comes from the name in French) technical committee "274-TCE: Testing and characterization of earth-based bui(5)g materials and elements" is responding to the need for new standardized test procedures, as for compression tests. Indeed, there are still no standardized test procedures for compression tests of RE in Europe and this acts as a barrier to the development of earth construction [10].

For the design of any building project, compressive strength (CS) is a major parameter. This is particularly true for non-standardized and natural materials as earth. Indeed(2)me authors [11–13], as well as regulations (e.g. [14]), recommend the application of compression tests before the execution[illegible]E buildings or during the execution for quality control [15].

This leads to different issues. Firstly, as earth is a natural and non-industrial material, a statistical characterization of the CS is required, for which at least three or four samples should be tested (see for example the appendix D "design assisted by testing" of Eurocode 0 [16]). Then, as it has been shown by different authors [17,18], RE compressive strength is highly dependent on the water content, through the suction, which evolved considerably between the execu(2)of the walls and the utilization of the building. A relation between suction and CS, to predict the latter through Mohr-Coulomb criterium, have been investigated [19].

Therefore, to design a building made with RE, it is useful to estimate its CS for different water content to assess the drying kinetic and the potential variation of the indoor air relative humidity of the building. To characterize an earth for the design of a building, it is then required to test a large number of samples.

Other parameters influencing the CS already have been investigated. The dry density of the material, linked to the energy of

Figure 6.81: Extracts from the abstract and introduction of the article (Pelé-Peltier et al., 2022a), the upper frame corresponds to the abstract while the other one corresponds to an extract of the introduction

5.3.1. Extracts (1)

In these extracts, it is observable that I attempted to situate. Indeed, in both series of extracts (abstract and introduction), I situated, at least partially, the approach of earth construction of the article in a Circular Economy (CE) frame (in particular, using local and "unstabilised" earth material), in comparison with other approaches ("mixing materials from quarries"). However, I would not write the following sentence anymore "Rammed Earth (RE) as a construction material fits perfectly into the circular economy concepts …". Indeed, such an assertion carries the idea that RE is intrinsically circular.

However, this depends on the approach adopted. Figure 6.82[171] provides more insights on earth construction in a CE framework. Degrees of circularity are often described using the "9Rs framework" – from the worst to the best: *Recover, Recycle, Repurpose, Remanufacture, Refurbish, Repair, Reuse, Reduce, Rethink, Refuse* (Kirchherr et al., 2023; Potting et al., 2017). The CE should be divided between its conceptual perfect form, which should be targeted, compared with its realistic imperfect form, as the use of virgin resources is inevitable (Figge et al., 2023). Figure 6.82 therefore underlines that there are different versions of earthen construction, some of them being more environmentally and socially virtuous than others (Morel et al., 2021b; A. Ventura et al., 2022). With its great variety of methods and techniques, raw earth construction does not escape to this hierarchy of circularity and does not provide intrinsically a circular material. This makes it essential, in every research, to systematically situate and specify the kind of earthen construction to discern how much it falls, or not, within the scope of "greenwashing" (Willis et al., 2023). Presenting RE as intrinsically circular is therefore first untrue. Additionally, it might hide the different visions of rammed earth construction (or more broadly earth construction) carried by the different groups of professionals as defined by Villain (2019). For example, it may conceal the controversy between the will to industrialize and the will to keep earth construction in the craft industry, which could have different consequences on the degree of circularity of earth construction. Figure 6.82 could however be useful as one way to situate the approach adopted for further research, from a CE perspective. The improvement of this CE framework could be a topic of further research. Of course, other frameworks laying on other concepts (e.g. sustainability or planetary limit) could also be investigated.

[171] This figure will be published under Pelé-Peltier, A., Goizauskas, J., Under review. Toward a situated understanding of challenges in the design and construction of circular raw earth buildings: the case study of a rammed earth office building in France.

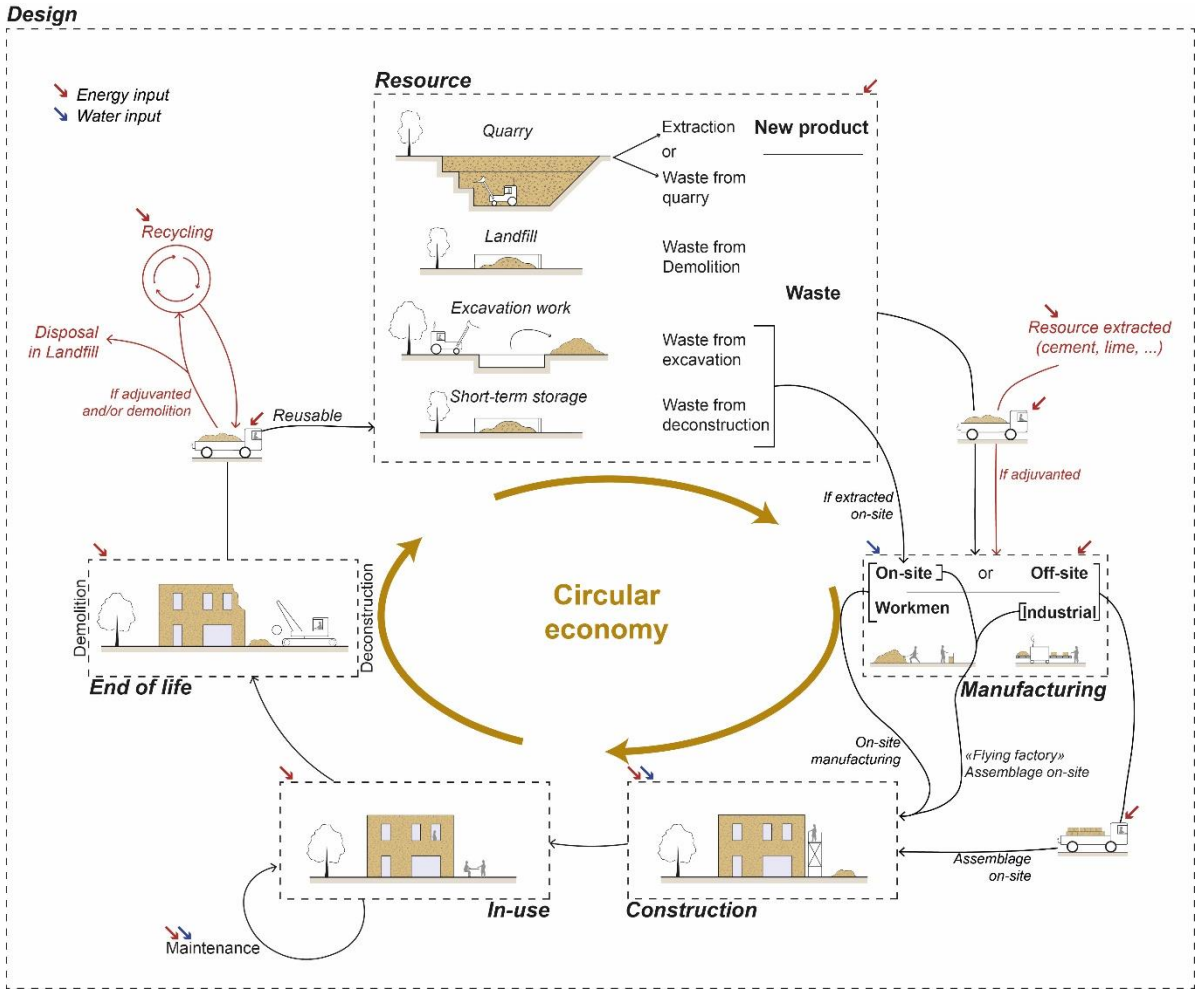


Figure 6.82: Schematic representation of a circular framework, with various versions of earth construction. Differentiation has been made to highlight the use of hydraulic binder as an adjuvant (texts and arrows in red) as it adds a resource extraction and a recycling or disposal step (source: author) will be published under (Pelé-Peltier and Goizauskas, Under review)

5.3.2. Extracts (2)

Extract 2 is related to the justification of focusing on compressive strength. In the abstract, I attempted to situate at least partially by precising that measuring compressive strength by lab testing on representative specimens is crucial for "*non-common buildings*". This can allow the reader to notify that it might not be needed for any buildings. On the contrary, in the extract of the introduction I did not situate at all as I wrote "*For the design of **any** building project, compressive strength is a major parameter*". I would not write this down today as, although compressive strength is indeed a major parameter for most buildings in Europe (so considering the European normative context of design), and was an important parameter in the case study, it might not be crucial for any buildings worldwide, or at least according to the scale of the buildings. Therefore, I could rewrite the sentence, for instance, as follow: "*In the European normative context of structural design based on Eurocodes, compressive strength is a major parameter for most of the building*". Besides, I would not write neither the following sentence "*Therefore, to design a building made with RE, it is useful to estimate its compressive strength*

for various water content to assess the drying kinetic and the potential variation of the indoor air relative humidity of the building". Indeed, while it was useful for the case study analysed and might be transferable for similar building scales and context, it is not for any RE buildings.

5.3.3. Extract (3)

This extract from the abstract can be seen as an attempt to situate the knowledge developed from economic perspectives. However, if I had to rewrite it today, I would be more precise. Indeed, it has been shown in Chapter 2 that the high cost of earth construction can only be considered a potential barrier in high-income countries, while earth construction is considered on the contrary low cost in low-income countries. Therefore, I would be more precise on the economic context in which this could help to reduce projects' costs, while on the contrary in low-income countries, recommending laboratory testing might increase projects' costs. I would also specify that it is more the laboratory testing costs that would be decreased than the project costs. Indeed, the first might be marginal in the project's costs and in particular it was negligible compared to the total case study budget. As shown in Chapter 5, the costs of the characterization raised issues more related to organizations and contractualisation between stakeholders (e.g. who should pay the characterization? Problem of contractualization… etc).

5.3.4. Extract (4)

In this extract, I implicitly took the position in favour of the development of standards that would not imply the creation of standardized products (See section 2.2). I still own it today as I think that it is consistent with my values. However, in a situated knowledges perspective that require transparency on the interaction between values and research, I should have notified it.

5.3.5. Extract (5)

I recognize that I fell into a similar lack of situating identified in some literature that introduces their articles with hypothetical barriers to earth construction. At least I situated it in Europe, which might be truer than in other places of the world (as shown in Chapter 2), however, it is not accurate enough. If I had to rewrite it today, I would write "*There are no standardized test procedures for compression tests of RE in Europe, considering the European normative context and design approach, this could be a barrier for structural designers willing to build with earth*."

5.4. Conclusion of the section

This section highlighted the necessity of situating the knowledge produced in Chapter 1 by the metaphor of the modest witness. In other words, knowledge should be situated in a complex historical trajectory and as part of socio-political realities. This knowledge was then situated among the process

described in section 4, itself situated among different design and standardization approaches (particularly performance and prescriptive) described in section 2. Finally, a discussion was proposed, in a reflexive approach, on the introduction of the published article relating to the knowledge produced in Chapter 1. Indeed, it has already been highlighted throughout the thesis that the introductions of articles can hide the values of the researchers and the biases linked to a lack of situating the research. Considering this, some improvements to the introduction have been proposed from the perspective of the situated knowledges theory. This is an important outcome. Indeed, the article was published in a relatively good journal (Case studies for construction material, open-access journal, Elsevier BV, Q1 journal with h-index of 47), however, neither the co-authors, nor the reviewers, nor the editors have commented on the above issues. No comment has been made on these issues and more broadly, as it has been repeatedly highlighted in the thesis, lack of situating is often carried in the introduction of articles in the earth construction field. Therefore, this might express a dominant vision in earth construction field. In that case, this thesis, by following a path "a little bit outside" of the civil engineering discipline in earth construction (by the methods and epistemology chosen) has helped to identify this bias.

> *"starting off research from 'outside' such a field, discipline, or society – even from just a little bit outside, such as on the margins – can enable the detection of the dominant values, interests, and assumptions in existing knowledge claims" (NagyHesse-Biber, 2012, p. 60).*

However, further research would be needed to understand and strengthen this hypothesis of having identified a dominant vision. To do so, a systematic review of introductions of earth construction articles could be performed.

6. Conclusion of the Chapter

To conclude, this chapter first described different philosophies of design methods (performance or prescriptive) on which the creation of standards can be based. These methods have socio-political implications. In particular, it was highlighted that groups of professionals use performance approaches to ensure the current important role of artisans in the construction process, as well as the possibility of using local earth. These different positionings explain why the question of creating new standards to overcome the barrier, represented by the absence of standards, is not so simple and these socio-political implications must be accounted for. This helped to situate the "design-by-testing" approach of the case study, being a performance approach that effectively places the masons in a central role. It was important to situate this approach, as such could be basement for future standardization. This approach, considered as a driver in the case study because it helped to overcome most of the barriers

concerning the load-bearing capacity of rammed earth, is rooted in five key steps: the materials sourcing, the prototyping, the characterizations, prefabrication and quality control. These key steps have been described and are interconnected. In summary, a specific mission was entrusted by the project owners to the masons who proceeded to the materials sourcing. The latter was constrained by the BREAAM label which imposed a distance of 30 km from the site and by urban context with polluted earths. During this step, coordination was necessary between the masons and the diggers and the masons and the design team, particularly for on-site storage. Once the earth had been selected by the masons, a characterization of the compressive strength of rammed earth specimens made by the masons was carried out to establish the design value and select the best performing earth. In parallel, prototypes were manufactured by the masons so that the design team and the project owners could validate the earth selected. From these prototypes, parameters were measured to continue the characterization, in particular to assess the compressive strength evolution according to the water content and the drying time of the rammed earth, useful for the quality control. The latter was mainly required by the control officers. It consisted of various checks including the checking of the dry density of the blocks and the drying process to inform the structural engineers who then authorized the masons to continue the implementation. Finally, monitoring the creep by surveyors and visual inspection by the masons was necessary to reassure the control officers. Indoor hygrothermal monitoring has been set up by the thermal engineers to reassure both the control officers (to verify that water content inside the wall do not increase too much during the service life) and the urban planners (to verify the thermal comfort of the building).

Finally, the method developed in Chapter 1 was situated in these key steps as having the potential for optimizing the characterization process. This allowed us to situate this knowledge among potential socio-political implications related to the design approach and more broadly to the creation of standards. Indeed, if this method was intended to be developed for the creation of standards, it could secure the role of the masons in the design process because the method is based on implementation parameters, which therefore depend on the masons. This need to situate was illustrated by an autocritique of the introduction of the published article related to Chapter 1. This corresponds to a reflexive approach which is a principle of the situated knowledge theories and could therefore contribute to moving towards situated research. The criticism of the introduction, for example, proposed to situate the research in the circular economy approach. This is an important point that has not been raised by any of the actors involving in the publication process, whether authors, reviewers or the editor. Introductions of articles present biases that raise a lack of rigour within the scientific publication process. It seems that introductions are often neglected. However, the bias identified and carried is important as it involves confounding values with “neutral” opinion. Further research could

therefore discuss how properly writing introductions of articles in earth construction field to avoid such bias

Conclusions, reflection and recommendations

Conclusions

The aim of this study was to attempt adopting epistemological reflections in civil engineering, specifically in earth construction field, based on the theory of situated knowledges[172]. It represents the originality of this thesis as such reflections is not common in these disciplines. This reflection raised from being involved in civil engineering research in earth construction field, and from different discussions with academics and professionals. These discussions led to the need to situate my researches, to which the theory of situated knowledges was useful. The starting point of this thesis, which is its first chapter, was a civil engineering research that conducted to a peer-reviewed article. Then, the objective was to situate the knowledge produced accordingly. To do so, it was chosen to investigate the barriers and drivers to the use of earth in construction. Indeed, where introductions of scientific articles are used to situate (consciously or not) research problems, to do so they often rely on hypothetical barriers to the use of earth. However, scientific evidences are never provided to support the barriers pointed out. Therefore, the hypothesis was that, if these barriers do not rely on scientific evidence, they may express the values of the researchers, without specifying these. Then, the articles' introductions may carry a bias related to a lack of situating, spotlighting a lack of rigour. In other words, these researches are situated as any research (which is the principle of situated knowledges) however they are presented as neutral. To discuss this potential bias, a literature review was first conducted to gather what the literature says about barriers and drivers to the use of earth in construction. Then, a case study analysis was proposed to discuss barriers and drivers at the scale of the design of a modern load-bearing rammed earth building. This case study analysis finally allowed us to situate the initial research produced.

The conclusions of this thesis are presented as answers to the research questions that were formulated in the introduction.

RQ2.1: How to assess compressive strength for small rammed earth specimens in laboratories representative to the on-site?

Compressive strength can be an important factor for structural engineers willing to design rammed-earth middle-to-high-scale buildings in the European context. While research already addressed the influence of different parameters on compressive strength (including water content, dry density, and clay content), almost none have investigated the scale effect. However, as design standards of rammed

[172] In this thesis, the theory of situated knowledges is understood as: any knowledge, including scientific, and their producers are situated in socio-political realities. Non-situated knowledge are only situated knowledges that ignores themselves. Therefore it is a matter of improving scientific rigour to *situate* the knowledge produced. This means to understand and then make visible the various and complex interactions between our studies and socio-political realities.

earth construction are often lacking, particularly in France, laboratory assessment of compressive strength may be necessary in some contexts. Consequently, small specimens being easier and cheaper to manufacture, it is interesting to assess the scale effect between small specimens and larger ones which are more representative of the onsite. In particular, when using earth containing large grains, as is often the case for rammed earth construction, these large grains can cause problems of heterogeneity for small specimens. Therefore, a specimen manufacturing method based on onsite key parameters (dry density and manufacturing water content) establishing a similitude relation was developed. Different sievings (12, 20, 30 and 50 mm) of the same earth were used to manufacture 66 specimens of different geometries and sizes to validate the similitude relation. From the analysis, multiple conclusions can be observed. The geometry of specimens (cylinders vs. prisms) does not affect the compressive strength. Therefore, cylinders may be preferred as they are easier to manufacture rammed earth specimens. For the same grain size fraction (0/20 mm), similar results can be obtained for two different sizes of specimens (cylinders of 15 cm of diameter and 30 cm of height, compared with prisms of 30x30 cm^2 of section and 60 cm of height). This might indicate that a ratio of 7.5 between the smallest length of the specimens and the biggest grains is enough to obtain homogeneous specimens compared to the common ratio of 10 used. Further research, on different earths could be carried out to define more precisely this ratio. Finally, the similitude relation, established with three equations to define equivalent parameters, allowed us to reach similar results between small-scale specimens and full-scale specimens, whatever the sieving applied to the earth to make these specimens.

RQ2.2: Are there and what are the barriers and drivers to the use of earth in construction?

An extensive literature review along with the analysis of the design of a showcase load-bearing rammed earth building have been carried out to address this issue. While 72 documents related to this research question have been found in the scientific literature, no synthesis of this literature existed yet. Additionally, the analysis of the methods of the documents highlighted that none extensively investigated a single case study.

The literature points out multiple barriers and drivers that can be categorized under five categories: technical (material resource, material's properties and design, construction, and maintenance phases), economic (cost and market), political (regulation, norms and government support), organizational (coordination, skills and education) and socio-cultural (perception, awareness). However, most of these barriers and drivers can be discussed according to various parameters. Indeed, it depends on the socio-economic context (the cost of earth construction is considered a barrier in high-income countries and a driver in low-income countries). It also depends on the geographic context, the specific technique considered (Rammed earth, compressed earth blocks, adobe, …), the normative and

regulation context and the stakeholder's perspective. The way these barriers are interpreted influence the path considered to overcome those. For instance, some properties of the material (such as sensitivy to water) are sometimes depicted as technical barriers. However, they could simply be factored in the design (as it was in the case study for erosion due to water sensitivity). Hence, a technical problem (how to decrease the water sensitivity of the material?) to a problem of professional trainings (how to transfer knowledge for proper design). Additionally, barriers that are depicted in the literature do not mean that they are impossible to overcome. This is illustrated by the case study in France, while in a context of lack of standards, often also depicted as a barrier, the stakeholders nevertheless succeeded in constructing a load-bearing rammed earth two-storey building. Of course, this achievement is based on different facilitating factors (drivers): (1) close collaboration during the design between various stakeholders such as architects, structural engineers, thermal engineers, academics and masons; (2) a favourable context of the case study as part of a larger project offering financial and time flexibility for both designers and project owners; (3) and the development of a design-by-testing method, resulting from negotiation between the design team, the control officers and the project owner, which is based on five key steps (materials sourcing, characterisation, prototyping, prefabrication and quality control).

This achievement also comes with obstacles faced by designers: (1) questioning rammed earth out of scepticism; (2) the questioning of the load-bearing capacity of the rammed earth, due in particular to the lack of standards and the difficulties of justification, which led to an unnecessary, time-consuming and costly procedure for developing standards (this procedure, however, helped to achieve consensus on the design-by-testing method).

Finally, it has been outlined that the literature on the topic often misses to situate their research which represents a bias in the analysis of the barriers and drivers. For instance, studies investigating in general the barriers to the development of earth in construction do not situate themselves in the dominant vision of "mainstream construction" which means a perspective of industrialisation of earth construction. However, other perspectives could exist that are currently made invisible by this literature. For instance, earth construction development could be considered in a CE framework.

This underlines that studying barriers and drivers is a complex issue that needs proper conceptualization.

RQ2.3: How to study barriers and drivers to the use of earth in construction?

As it has been outlined that literature on barriers and drivers lacked conceptualization, a conceptual framework has been developed in this thesis. This conceptual framework, although quite simple, has

the advantage of making visible the bias identified for lack of situating. Indeed, it is proposed to investigate barriers (or drivers) as elements that create difficulties (or facilitate) for an object to achieve an objective. All of this is contextually dependent (geographical, socio-economic, urban vs. rural, formal vs. unformal, etc…). It is also dependent on stakeholders' perspectives (different views according to the type of stakeholders, for instance between architects or project owner, and different views according to a group of stakeholders sharing similar values, for instance, artisanal vs. industrial development perspectives). Additionally, the scale of the study should be considered. Therefore the "object" can refer to earth construction in general, but also to specific fields, such as CEB (compressed earth blocks) production, or specific techniques, such as rammed earth. The "objective" can be one perspective of the development of earth construction, for instance in the current mainstream construction or including circular economy principles. The "objective" can also be the acceptance of a specific technique. Specifying all these parameters might be difficult. For instance, investigating barriers to the development of earthen construction requires first understanding from which development perspective the study is situated. This might not be easy, as sociological scientific studies would be needed to first identify what are the different visions. Therefore, a methodology based on a single case study, which is intrinsically situated, has been proposed. Barriers and drivers have been redefined accordingly: the barriers (or drivers) to the use of earth in our case study should therefore be understood as the set of challenges and constraints (or facilitating factors) faced by stakeholders to reach consensus on the technical solution of load-bearing rammed earth facades, given the location of the building and its context. Then, barriers and drivers will measure what separates the conceptual wall element (during the design) from the final wall element, corresponding to the delivery. Challenges and constraints may be related to technical, economic, political, organisational and socio-cultural factors or a combination of these, and may depend on the context of the building and the normative system.

RQ1.1: What are the biases related to non-situated knowledge in the earth construction field?

It has been observed in the literature that many earth construction scientific articles start with hypothetical barriers (without scientific evidence) to justify their research. For instance, many articles investigating earth adjuvantation, to improve water resistance, spotlight in the introduction that low durability represents a barrier to the development of earth. However, the conclusions on the investigation of barriers highlight that (1) first considering "barrier to the development of earth" is not precise enough and represent a lack of situating (i.e. lack to make visible the complex interaction with socio-political realities which hide potential other paths), (2) second, these "barriers" are context-specific. This is an important bias carried by non-situated knowledge (in other words, "situated

knowledge that ignores itself"[173]). To illustrate, when putting forward the following assertion "the development of earth construction is limited due to low durability, therefore it is interesting to study adjuvantation of earth" represents at least two problems. First, it is untrue, because not situated enough and too vague so it represents a lack of rigour (which development are we talking about?). Second, it might carry a dominant vision (namely solving hypothetical technical barriers by technical means) that hides potential other research (for instance, research on proposing proper design solutions, or research on educating stakeholders about the specificities of the material, etc…). Through the prism of the theory of situated knowledges, further research on earth construction could be carried out to analyse the visions carried by the introductions of scientific articles in the field of earth construction.

RQ1.2: What could be situated research in the earth construction field?

The whole point of this thesis was to highlight that situated knowledges theory can be useful for earth construction research. To achieve this, the knowledge produced that addressed the first research question has been, to some extent, situated thanks to a large detour of analysing barriers and drivers to the use of earth in a case study. Of course, further research in earth construction cannot always make such a detour. However, the autocritique of the introduction of my first scientific publication related to the first research question is an avenue to follow for situated research. Situated research could be understood as research that recognizes being part of socio-political realities, and having therefore implications on them and related responsibilities. Identifying such implications is not easy, but making them visible as much as possible is necessary. To do so, one proposition could be to make a declaration of values (as it was done in this thesis) similar to the declaration of interests already existing in scientific articles. To appreciate better the socio-political interactions with our research, one way could also be to work with multidisciplinary teams (composed of social scientists, anthropologists, etc…) but also with various professionals (architects, masons, structural engineers, …) or citizens (with various backgrounds). In any case, the positivist philosophy often carried in the natural and physical sciences (consciously or not) which sees researchers as external to the world they observe no longer seems significant.

Finally, there is an aspect that has not been investigated in this thesis which is however major in situated knowledges theory. I have not investigated the potential bias related to my particular vision as a privileged individual (member of different dominant groups, in term of gender, race, etc.). This could contribute to my reflections for my future research. Additionally, this thesis do not claim to propose a method to perform situated research, but to open epistemological reflections in earth

[173] Quotation of Alessandra Quadrelli, see the introduction of the thesis.

construction field. Indeed, the thought of Donna Haraway, and more broadly feminist epistemologies, are quite complex and not yet implemented in our disciplines. Further research could therefore help to understand better how to include such reflections in physical and natural science.

Significant original contributions to knowledge

The significant original contributions to knowledge of this thesis can be summarized as follow:

- A similitude relation to manufacture scale-down rammed earth specimens representative to the onsite material has been developed.
- A bias has been identified in some of the studies investigating barriers and drivers to the use of earth in construction. This bias corresponds to a lack of conceptualisation that can lead to non-situated research.
- A conceptual framework has been developed to tackle this bias. This conceptual framework proposes to consider an object that need to attain on objective, in a specific context, implying different stakeholders' perspectives. Describing properly the object, the objective, the context and the stakeholder's perspective is a way to situate the study.
- A method, using this conceptual framework, of a single case study analysis has been proposed. A proper definition of barriers and drivers has been provided accordingly.
- A lack of situating have been identified in some introduction of scientific articles on earth construction. Indeed, to situate their studies, they often integrate hypothetical barriers, without scientific evidence. However, this thesis has shown that these barriers cannot be considered as describing realities, which therefore hide a bias.
- Avenues for reflection on this lack of situating have been proposed, in particular by discussing introductions of articles.

Recommendations for future research

The following recommendations for future research can therefore be made for compressive strength research, barriers and drivers research, and both:

For research on compressive strength, the following recommendations can be made:

- As the study investigated only one earth, future research could improve or validate the similitude relation by investigating other types of earth, or even other implementation

techniques (e.g. cob). Besides, future research could establish similitude relations in the case of porous grains as only non-porous grains have been considered in this thesis.

For research on barriers and drivers, the following recommendations can be made:

- Future research on barriers and drivers could use the conceptual framework developed in this thesis to situate explicitly.
- Further research could establish a prospective to identify and analyse the possible development perspectives of earth construction so barriers and drivers can be studied accordingly (e.g. using a circular economy framework, using environmental regulation framework, …).

For both, the following recommendations can be made:

- As situating research is a continuous reflection between values carried by researchers and their research, future research should take over this theory to develop a new framework of analysis (in earth construction or more generally in civil engineering).
- Future research could establish systematic research on the identification of values in introductions of earth construction articles.

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Appendix

Appendix A1: Justification of the hypothesis that the water between the grains and the matrix is negligible

In the thesis of Longfei Xu (2018), the sorption-desorption curves have been drawn using DVS method for three soils with different clay content (17%, 26%, 35%), as represented in the following figure:

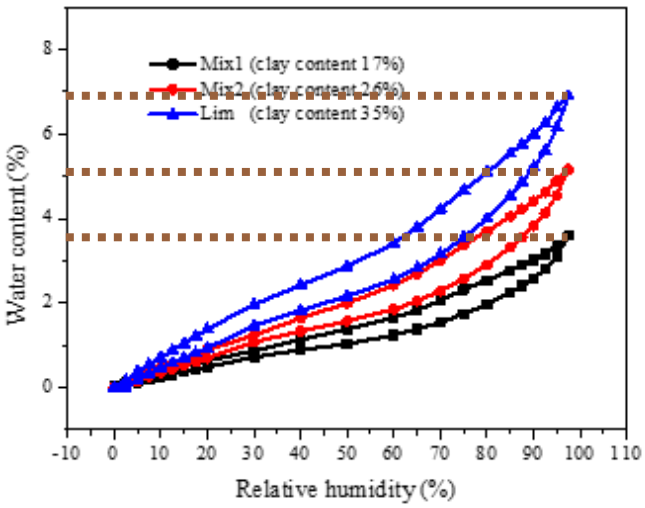


Figure A1.83: Sorption-desorption curves for three soils with different clay content, extracted from (Longfei XU, 2018, p86)

The earth used in the thesis of Longfei Xu come from the same area in France and are typical earths found in the region. To verify the hypothesis that the water at the interface between grains and clay matric, the following condition should be verified:

$$\frac{m_e}{m_{s_c}} = \frac{w}{C} = constant \quad \text{(A1)}$$

Where, m_e is the mass of water, m_{s_c} is the masse of clay, w is the water content at 95% relative humidity, and C is the clay proportion. From the Figure A1.83 and this equation, the following table can be obtained, highlighting a constant ratio between the water content and the clay content within the margins of error.

Table A1.20: Results obtained from Figure A1.83 and equation (A1)

Clay content	W at 95% HR	w/C
35%	7%	20%
26%	5,1%	19,6%
17%	3,6%	21,2%

Appendix A2: Reproducibility of the approach (Chapter 1)

To reproduce the approach of similitude used in this paper, the below indicative tick points can be followed:

- For a given earth used in situ, called reference earth
- Determine: the grain-size curve (to obtain the per cent of passing P(X), where X is the chosen sieving diameter for the study), the porosity of the grains of size higher than X (immersion test) and the density of the grains $\rho_G(X/d_{\max(f(\ ))})$ (through hydrostatic weighing), where d_{max} is the diameter of the biggest grain contained for in the reference earth.
- Determine the reference parameters (manufacturing dry density ρ_{ref} and the manufacturing water content w_{ref}). These parameters can be obtained from the on-site for the case of a real construction project, or in laboratory through proctor tests for example.
- Calculate the equivalent parameters (manufacturing dry density $\rho_d(X)$ and manufacturing water content $w(X)$) using the two following equations.

$$\rho_d(X) = \frac{P(X)}{\frac{1}{\rho_{ref}} - \frac{1-P(X)}{\rho_G(X/d_{max})}} \quad \textbf{(A1)}$$

where $P(X)$ is the mass proportion of material with grain size lower than X within a volume of the reference earth; $\rho_G(X/d_{max})$ is the dry density of the grains higher than X within the volume V_{ref}, the latter corresponding to the volume of reference earth.

$$w(X) = \frac{w_{ref}}{P(X)} \quad \textbf{(A2)}$$

- Manufacture the specimens: preferably cylinders, with an aspect ratio of 2. In order to assess the similitude relationships, the same size should be chosen for the different specimens. Ideally, the two set of specimens (specimens made with sieved earth C_X and specimens made with reference earth C_{ref}) should be manufactured under the same conditions.
- To draw the results for the sieved earth, the following correction concerning the water content should be applied:

$$w_{cor} = P(X).w \quad \textbf{(A3)}$$

Where w is the measured water content of the specimen.

- Finally, compare the results between the sieved earth specimens and the reference

Appendix B: Details of the papers selected for the literature review (Chapter 2)

					Geography		Material		Methodology		
	Author	**Year**	**Paper's focus**	**name of the journal**	**Countries (ISO 3166)**	**Economies**	**Technics**	**S/ UnS / B**	**Qual - Quant - Mixed**	**RM**	**Details**
Group 1: Papers aiming at identifying barriers and drivers to the use of earth in construction	Hafez et al.	2023	Barriers and enablers for scaled-up adoption of compressed earth blocks in Egypt	BRI	EG	Lower-middle-income group	CEB		Mixed	Q+I	Two stages survey among experts (22 respondents for the first survey, 17 for the second), 5 interviews among survey panel / architects, CEB manufacturers, academics
	Strazzeri and Karrech	2023	Use of rammed earth construction technology in Perth and south-west of Western Australia	ClM	AUS	High-income group	RE	B	Mixed	Q+I	Qualitative and quantitative survey addressed to three sub-groups (29 architects, 6 engineers and 13 builders)
	Nina et al.	2023	Earthen construction: acceptance among professionals and experimental durability performance	CM	PT / BZ	High-income group	RE / CEB	UnS	Quant	Q	Questionnaire's survey (59/500 respondents) among students and professionals of architecture and engineering from Brazil and Portugal
	Lakys et al.	2022	Investigating drivers for the use of Compressed Earth Blocks in Kuwait	CSCM	KWT	High-income group	CEB	UnS	Quant	Q + SA	Pilot study with 18 responses for practionners and 39 responses for clients helped to build two questionnaires : one for practionners (52 respondents: 40 designers, 1 consultant, 7 contractors, 4 project managers), one for clients (102 respondents : 11 owners, 18 investors, 73 end-users) / no RR
	Gomaa et al.	2022	Investigating challenges associated with 3D printing (digital manufacturing) for earth construction	JCP	World	N/A	3D printing	S	N/A	CR	

	Dorado et al.	2022	Contemporary difficulties and challenges for the implementation and development of compressed earth block building technology in Argentina	JBE	AR	Upper-middle-income group	CEB	B	Mixed	Q+I	Survey 53 respondents (2 machinery manufacturer, 7 builder and self-builder, 7 CEB manufacturer, 15 Professional, 22 Academic) RR=65% / In-depth interviews 9 respondents (among the 53)
	Zami	2021	Barriers hindering acceptance of earth construction in the urban context of the United Kingdom	AEDM	GB	High-income group	EBMM	B	Qual	D + I	Delphi method (22 participants, international experts), 6 interviews UK experts (including 5 academics)
	Zami	2021	Enablers supporting acceptance of earth-based material in UK urban housing sector	AEDM	GB	High-income group	EBMM	B	Qual	LR+ D+I	Delphi method (international experts), 5 Interviews (UK experts)
	Morel et al.	2021	Barriers to earth construction	PTRS	FR/GB/BE /SP	High-income group	EBMM	UnS	Qual	I	20 semi-structured interviews with various stakeholders
	Zawistowski et al.	2020	Evolving Vernacular: Reinventing Rammed Earth in the Context of Twenty-First Century Seismic Regulation	TAD	FR	High-income group	RE	UnS	Qual	CS	One case study
	Kulshreshtha et al.	2020	Potential and current status of earthen architecture in rural India	CBM	IN	Lower-middle-income group	EBMM	B	Qual	I	40 various stakeholders I
	Zami	2020	A conceptual framework outlining factors affecting the acceptance of earth as a sustainable building material in the United Kingdom	EJSD	GB	High-income group	EBMM	B	Qual	LR+ D+I	Delphi method (international experts), 5 Interviews (UK experts)
	Ben-Alon et al.	2020	Integrating earthen building and methods into mainstream construction	JGB	World / US	High-income group	EBMM	B	Mixed	Q+I	126 (experts and end-users) Q (RR not notified), 10 experts I
	Totla et al.	2019	Sustainable rammed earth structure: a structurally integral, Cost-effective and eco-friendly alternative to conventional construction materials	IJITEE	IN	Lower-middle-income group	RE	B	Qual	CS + CA	Only one field visit, this paper provide an insight of challenges and drivers in India. However, the methodology is insufficiently described / no distinction are made between stabilised and unstabilised

	Adeniyi and Mohamed	2019	Investigating potential green materials to improve cost effectiveness for low-cost building construction in Nigeria	IJRTE	NG	Lower-middle-income group	Adobe	NN	NN	NN	
	Shahabadi et al.	2019	Relationship of economic and environmental factors with the acceptance of earthen architecture technology: A case study of young educated couples in Yazd, Iran	TS	IR	Lower-middle-income group	EBMM	B	Quant	Q	145 young educated couples in Yazd
	Mileto et al	2019	The influence of geographical factors in traditional earthen architecture: The case of the Iberian Peninsula	Sust.	PT / SP	High-income group	RE / adobe / WD	UnS	Quant		Geographical analysis
	Monzur	2018	Study of the reasons for the shift from traditional (using earth material) to modern (using bricks) housing	IJAR	BD	Lower-middle-income group	Mud	B	Qual	I	150 villagers Questionnaire survey
	Bradley et al.	2018	Compressed stabilized earth block shell housing performance considerations	PPSDC	ZA	Upper-middle-income group	CSEB	S	Qual	LR+ CS	Three case studies (three typologies of low-cost housing)
	Gallipoli et al.	2017	Geotechnical perspective of raw earth buildings	AG	N/A	N/A	EBMM	UnS	N/A	LR	
	Adegun and Adedeji	2017	Economic and environmental benefits of earthen materials in Africa	FAR	Africa	Low-income and lower-middle-income group	EBMM	B	N/A	LR	Literature review specific to african countries (136 academic outputs including journal article, conference proceeding, book chapter, thesis/dissertation and report)
	Cataldo-born et al.	2016	Obstacles and motivations for earthbag social housing in Chile: Energy, environment, economic and codes implications	RC	CL	High-income group	Earthbag	S	Mixed	LR + CS	Environmental and economic comparison based on case study
	Spisakova and Mackova	2015	Barriers to the use of traditional materials in modern methods	SSP - JCE	SK	High-income group	TBM	B	Quant	Q	102/463 respondents (RR = 22.03%) among potential investors for construction of houses in Slovakia

	Sameh	2014	Promoting earth architecture as a sustainable construction technique in Egypt	JCP	EG	Lower-middle-income group	EBMM	UnS	Qual	CS+CR	Multiple case studies of buildings
	Owino et al.	2014	Assessment and improvement of ISSB technology	IJTD	UG	Low-income group	ISSB	S	Quant	Q	53/60 (RR=88.33%) respondents Engineers, technicians and craftsmen
	El-Sawalhi and Ajwa	2013	Mud building in the Gaza Strip	IJCM	Gaza strip	Low-income group	SEB / adobe	B	Quant	LR+Q	48 contractors and 5 clients Q (RR not notified)
	Foruzanmehr	2013	Residents' perception of earthen dwellings in Iran	IJUSD	IR	Lower-middle-income group	Adobe	UnS	Mixed	Q+I	Questionnaires (360 respondents, end-users living in earth dwellings and respondents living in non-traditional dwellings) Interviews (12 end-users, respondents to the questionnaire + 12 experts, architects, academics, professional builders and local authorities)
	Niroumand et al.	2013	A guideline for assessing of critical parameters on Earth architecture and Earth buildings as a sustainable architecture in various countries	RSER	US/GB/IN/AU/IR/MY	Lower to high-income group	EBMM	NN	Quant	LR+Q	763/1480 (RR=51%) ICOMOS members Q
	Danso	2013	Benefits and problems of earth construction in Ghana	IJST	GH	Lower-middle-income group	Mud	UnS	Quant	Q	50/65 (RR = 76,9%) households respondents, structured Q
	Lu and Liu	2013	Rammed earth construction	AMM	CN	Upper-middle-income group	RE	UnS	N/A	CS	Traditional earth construction in China CS
	Pacheco-Torgal	2012	Earth construction: Lessons from the past for future eco-efficient construction	CBM	N/A	N/A	EBMM	B	N/A	LR	
	Zami	2011	Inhibitors to stabilised earth construction	JBA	International	N/A	SEBMM	S	Mixed	LR+D	10/34 various stakeholders (Academician, Practitioner, Practioner researcher) D
	Zami	2011	Drivers that help adopting stabilised earth construction to address urban low-cost	EDS	International	N/A	SEBMM	S	Mixed	LR+D	10/34 various stakeholders (Academician, Practitioner, Practioner researcher) D

			housing crisis: An understanding by construction professionals								
Group 2 : Papers aiming at describing one category of barriers or drivers	Samarasinghe and Falk	2022	Investigating reasons for the lack of awareness of earth construction in New Zealand	B	NZ	High-income group	EBMM	B	Mixed	I+Q	7 experts interviews (builders, end-users, academicians), 79 members of Earth Building Association New Zealand Q (RR not notified)
	Fabbri et al.	2021	An overview of the remaining challenges of the RILEM TC 274-TCE, testing and characterisation of earth-based building materials and elements	RILEM TL	N/A	N/A	EBMM	B	N/A	LR	
	Marsh et al	2021	The state of earthen housing worldwide: how development affects attitudes and adoption	BRI	International	N/A	EBMM	B	Quant		National demographic data analysis
	Fernandes et al.	2019	Passive strategies and thermal performances of rammed earth in Portugal	RE	PT	High-income group	RE	UnS	N/A	ECS	ECS in PT, monitoring thermal performance of building
	Fabbri	2018	Assessing the performance of earth building materials: A review of recent developments	RILEM TL	N/A	N/A	EBMM	B	N/A	N/A	
	Hughes et al.	2017	Perceptions of CEB	JGB	US	High-income group	EB	UnS	Mixed	Q+I	30 contractors (snowballing sampling = no response rate) Q / 2 professional I
	Gomes	2014	Unstabilized rammed earth: Characterization of material collected from old constructions in south portugal and comparison to normative requirements	IJAH	PT	High-income group	RE	UnS	N/A	LR	Comparison between normative documents thresholds and parameters of Unstabilised rammed earth specimens collected from six constructions
	Hurol et al	2014	Building code challenging the ethics behind adobe architecture in north cyprus	SEE	CY	High-income group	adobe	UnS	Qual	CS + I	Two case studies and one interview
	Swan et al.	2011	Sustainable earthen and straw bale construction in north american buildings: Codes and practice	JMCE	US / CA	High-income group	EBMM	B	N/A	LR	Literature review of existing building codes in north america

	Williams et al.	2010	Feasability of earth block masonry in UK	JBA	GB	High-income group	EB	B	N/A	LR	
	Gado et al.	2010	Feasability of earth architecture in Egypt	IBI	EG	Lower-middle-income group	Adobe	UnS	Qual	CS+I	Field trip to oasis / 18 I
	Zami and Lee	2010	Economic benefits of contemporary earth construction in low-cost urban housing - State-of-the-art review	JBA	N/A	N/A	EBMM	S	N/A	CR	
	Hadjri et al.	2007	Attitudes towards earth building for Zambian housing provision	PICE-ES	ZM	Lower-middle-income group	EBMM	NN	Mixed	CS+I +Q	20 end-users surveyed CS / 22/60 (RR= 37%) respondents Q / 1 expert I
Group 3 : Papers mentioning barriers or drivers but without specific methodology	Laou et al.	2021	Hygroscopic and mechanical behaviour of earth bricks	MS	N/A	N/A	EB	UnS	N/A	N/A	
	Chauhan et al	2021	Benefit of Unsaturated soil mechanics approach on the Modeling of Early-age Behavior of Rammed Earth Building	M	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Moriset et al.	2021	Can earthen architectural heritage save us ?	BH	N/A	N/A	N/A	N/A	NN	N/A	Part of the paper is a review but most of the assessment are claims of the authors
	Giada et al.	2019	Hygrothermal Properties of Raw Earth Materials: A Literature Review	Sust.	N/A	N/A	EBMM	UnS	N/A	N/A	
	Champiré et al	2016	Impact of relative humidity on the mechanical behavior of compacted earth as a building material	CBM	N/A	N/A	N/A	N/A	N/A	N/A	
	Egenti et al.	2014	Pilot study of CEB use in Nigeria	IJSBE	NG	Lower-middle-income group	EB	Both	N/A	N/A	This paper refers to a conference to discuss briefly the perception of CEB and CSEB
	Bui et al.	2009	Compression behaviour of non-industrial materials in civil engineering by three scale experiments: The case of rammed earth	MS	N/A	N/A	RE	N/A	N/A	N/A	

	Sha et al.	2000	Sustainable construction in China	BRI	CN	Upper-middle-income group	EBMM	UnS	N/A	N/A	
Name of journal		*Journal of Building Engineering (**JBE**), Materials and Structures (**MS**), Technology Architecture + Design (**TAD**), Renewable Energy (**RE**), Sustainability (**Sust.**), International Journal of Innovative Technology and Exploring Engineering (**IJITEE**), International Journal of Recent Technology and Engineering (**IJRTE**), RILEM Technical Letters (**RILEM TL**), International Journal of Cultural Heritage (**IJAH**), Jordan Journal of Civil Engineering (**JJCE**), Structural Engineer (**SE**), Journal of Green Building (**JGB**), Science and Engineering Ethics (**SEE**), Materials (**M**), Practice Periodical on Structural Design and Construction (**PPSDC**), Built Heritage (**BH**), Buildings (**B**), Building Research and Information (**BRI**), Architectural Engineering and Design Management (**AEDM**), European Journal of Sustainable Development (**EJSD**), Construction and Building Materials (**CBM**), Journal of Green Building (**JGB**), Technology in Society (**TS**), Frontiers of Architectural Research (**FAR**), Revista de la Construccion (**RC**), Journal of Cleaner Production (**JCP**), Environment, Development and Sustainability (**EDS**), Journal of Materials in Civil Engineering (**JMCE**), Journal of Building Appraisal (**JBA**), International Journal of Technoscience and Development (**IJTD**), International Journal of Urban Sustainable Development (**IJUSD**), Case Studies in Construction Materials (**CSCM**), Construction Materials (**CM**), Cleaner Materials (**ClM**)*								
Material		*Cement Stabilised Interlocking Earth Blocks (**CSIEB**), Compressed Stabilized Laterite Bricks (**CSLB**), Earth Building Materials and Methods (**EBMM**), Stabilised Rammed Earth (**SRE**), Rammed Earth (**RE**), Interlocking Stabilised Soil Blocks (**ISSB**), Traditional Building Material (**TBM**), Stabilised Earth Blocks (**SEB**), Stabilised Earth Building Materials and Methods (**SEBMM**), Earth Blocks (**EB**), Wattle and Daub (**WD**) Stabilised (**S**), Unstabilised (**UnS**), Both (**B**)*								
Research method (**RM**)		*Questionnaire (**Q**), Interviews (**I**), Case Study (**CS**), Literature Review (**LR**), Experimental Case Study (**ECS**), Critical Review (**CR**), Delphi method (**D**), Exploratory Survey (**ES**), Cost Analysis (**CA**) / Qualitative analysis (**Qual**), Quantitative analysis (**Quant**) / Response Rate (**RR**), Statistical analysis (**SA**)*								
		*Not notified (**NN**), Not Applicable (**N/A**)*								

	Author	Year	Paper's focus	Countries (ISO 3166)	Economies	Technics	S/UnS/B	Qual - Quant - Mixed	RM	Details	Type of paper
Group 4: Conferences/Master's thesis/Grey literature	Aghimien et al.	2016	Drivers and Barriers for CSIEB for building construction in Nigeria	NG	Lower-middle-income group	CSIEB	S	Mixed	Q+I	57/60 (RR=95%) Q 10 I construction professionals	Conference paper
	Baiche et al.	2017	Earth construction in Algeria	DZ	Lower-middle-income group	SRE and adobe		Qual	CS+I	Two village CS (Traditional vs modern) with 25 dwellings studied in the traditional village against 22 in the modern one	Conference paper
	Fundi et al.	2019	Acceptability of ISBT in Kenya's construction industry	KE	Lower-middle-income group	ISSB	S	Qual	I	32 technology users and non-users I	Conference paper
	Kraus	2012	On perceptions of rammed earth	US	High-income group	RE	UnS	Quant	Q	Students and professionals (RR not notified)	Conference paper
	Samarasinghe et al.	2020	Promoting earth buildings through persuasive virtual reality	NZ	High-income group	EBMM		Qual	I	7 experts in earth construction (Artisan, Architects, Civil engineer, Academician, household…) I	Conference paper
	Van der Linden et al.	2019	Potential of earth architecture in Belgium	BE	High-income group	SRE and SEB	S	Qual	LR + CS	Two contemporary earth projects with architects interviewed CS	Conference paper
	Wright and Thorpe	2015	Use of advanced and green construction materials by small and medium-sized enterprises	AU/NZ	High-income group	RE + adobe		Quant	ES/Q	30/749 (RR = 4%) various stakeholders (Engineering, Construction, Architecture 50%) Q	Conference paper
	Barbacci	2020	Valorisation and underestimation of earthen architecture	AR/CO/CL/CR/PE	N/A	EBMM	NN	NN	NN	NN	Conference paper

	Mpakati-Gama et al.	2012	Barriers to the use of alternative materials in developing countries	Sub Sahara Africa	Lower-income group	SRE + SEB	S	-	-		Conference paper
	Zupancic	2012	Earth architecture practices in Slovenia	SI	High-income group	EBMM	N N	-	-		Conference paper
	Morel and Charef	2019	Barriers to the use of earth as a modern construction material	N/A	N/A	EBMM	N N	-	-		Conference paper
	Villar	2020	How to integrate earth construction into contemporary architecture?	FR							Master's thesis
	Harries et al.	2020	Codes and standards development for nonconventional and vernacular materials	USA	High-income group	EBMM	N N	NN	NN	NN	Book chapter
	Hassani	2018	Earth construction field in France	FR							Master's thesis
	Dick and Krahn	2015	Regulatory challenges and benefits of SRE in Canada	CA	High-income group	SRE	S	Qual	CS	Two CS in Ontario	Book chapter
	Schroeder	2012	Codes, standards and normative development for earth construction	W	Both	EBMM		Not applic able	CR	Review of standards dedicated to earth construction	Book chapter
	Schroeder	2016	Educations, Networking, Research and Standardization, Economic development	N/A	N/A	EBMM	N N				Book chapter
	AsTerre	2013	Study on obstacles toward the development	FR	High-income group	EBMM		N/A	N/A	Questionnaire survey (80 respondents: 41 contractors, 16 architects and	Report

			of earth construction in France							engineers, 12 formation organisms, 8 product manufacturers, 3 clients)	
	Wallis	2012	Modern rammed earth construction in China	CN	Upper-middle-income group	RE	S				Book chapter
	GT biosourcé	2012	Insurance system in construction and barriers associated for biosourced materials	GB/FR/DE	High-income group	Biosourced materials					Report
	Leylavergne	2012	Earth construction field in France	FR	High-income group	EBMM					Master's thesis

Appendix C1: Bullet point protocol used for the analysis of the document of the case study (Chapter 3)

Protocol:

1. Data sorting

1.1. Remove documents that are not related to the project

1.2. Rearrange emails chronologically in an Excel spreadsheet

1.3. Select important technical documents (end of phase, deliverables, milestones, key points).

2. First reading of Emails

2.1. Go through the document entirely

2.2. Identify key points of the phase

2.3. Note potential questions to ask

3. Second reading of Emails

3.1. Coding in Nvivo or drafting the story board on the board (Figure C1.84)

3.2. Identify key points of the phase

3.3. Note potential questions to ask

4. Third reading of Emails

4.1. Coding in Nvivo or drafting the story board on the board

4.2. Identify key points of the phase

4.3. Note potential questions to ask



Figure C1.84: Picture of the analysis process: making a timeline of the project

Appendix C2: Example of question grid for the interviews (Chapter 3)

Introduction

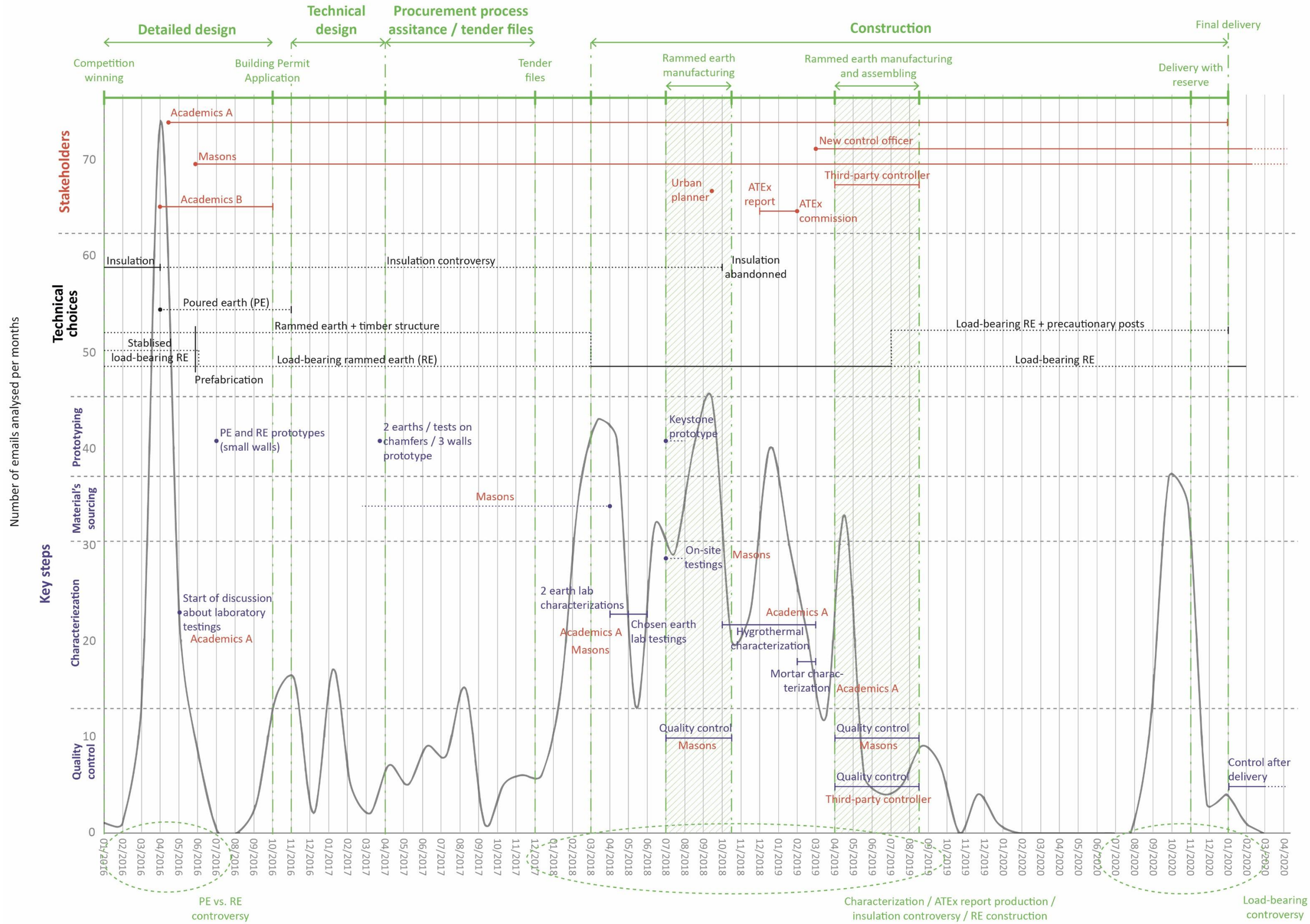
Presentation of the study / Consent for recording

In your opinion, what were the main problems encountered during the project? What solutions were found? What were the conditions for the project's success?

Complementary questions (adapted according to the interviewees and each interview process):

- Coordination problems or specificities in the project?
- Communication problems or specificities in the project?
- What were the problems/solutions related to the project's process?
- What were the key steps for the success of the project?
- Were there problems related to the contractualisation between stakeholders? Why? What solutions?
- Were there problems related to costs? Why or why not? What solutions?
- Were there problems related to norms or regulations? Why or why not? What solutions?
- Were there concerns about the use of earth in the project? Which one?

What were the key stakeholders of the project?


Detailed design
Technical design
Procurement process assitance / tender files
Construction
Final delivery
Competition winning
Building Permit Application
Tender files
Rammed earth manufacturing
Rammed earth manufacturing and assembling
Delivery with reserve
Number of emails analysed per months
Key steps
Stakeholders
Technical choices
Prototyping
Material's sourcing
Characteriezation
Quality control
Academics A
Masons
New control officer
Third-party controller
Urban planner
ATEx report
ATEx commission
Academics B
Insulation
Insulation controversy
Insulation abandonned
Poured earth (PE)
Rammed earth + timber structure
Load-bearing RE + precautionary posts
Stablised load-bearing RE
Load-bearing rammed earth (RE)
Load-bearing RE
Prefabrication
PE and RE prototypes (small walls)
2 earths / tests on chamfers / 3 walls prototype
Keystone prototype
On-site testings
2 earth lab characterizations
Chosen earth lab testings
Hygrothermal characterization
Mortar charac-terization
Start of discussion about laboratory testings
Quality control
Control after delivery
Third-party controller
PE vs. RE controversy
Characterization / ATEx report production / insulation controversy / RE construction
Load-bearing controversy

Appendix E: Different methods of design found in the literature (Chapter 6)

New Zealand standard

The NZS 4297 "Engineering design of earth buildings" introduces two categories of strength (New Zealand Standard (NZS), 1998, p. 429). The "Standard Grade" with a design compressive strength of 0.5 MPa and a little number of tests, and a "Special Grade" requiring more testing in order to obtain the characteristic strength of the material.

The New-Zealand standard NZS 4298 "materials and workmanship for earth buildings" provides a formula similar to the one in Eurocode to obtain the characteristic compressive strength (f') from the results of five unconfined compression tests:

$$f' = \left(1 - 1.5\frac{x_s}{x_a}\right) x_l \tag{4}$$

Where x_l is the lowest value of the test results, x_s is the standard deviation and x_a is the mean value.

The design value is not calculated from the characteristic strength. Here, the characteristic strength should be a target, for example for standard grade construction, a minimum of 1.3 MPa for at least 5 specimens tested with an aspect ratio of 1, should be obtained. Then, the design strength is provided by the regulation, not from the calculation. For a standard grade, the design value should be 0.5 MPa.

Considering the standard grade construction, with characteristic strength of 1.3 MPa and a design compressive strength of 0.5 MPa, we can calculate the partial safety factor by using the following formula given by Eurocodes:

$$f_d = \frac{f_c}{\gamma_m} \tag{5}$$

Then, an equivalent partial safety factor would be equal to 1.3/0.5 = 2.6.

Method proposed by Walker et al. (2005)

In his book, Peter Walker also proposes a performance approach to design rammed earth buildings, based on unconfined compression tests. The following formula is provided:

$$f_c = f_a - 1.65\sigma_{n-1} \tag{6}$$

Where, f_c is the characteristic compressive strength, f_a the average unconfined compressive strength and σ is the standard deviation of test specimens. This formula corresponds to the value at a fractile 5% of a normal distribution.

From the characteristic strength obtained, the resistance of the wall must satisfy the following equation:

$$N_d \leq (\phi f_c b t)/\gamma_m \quad (7)$$

Where N_d is the design compressive force, Φ is the capacity reduction factor depending on the slenderness ratio and the load eccentricity, γ_m is the material partial safety factor and b.t is the section of the wall.

Partial safety factor ranged from 3 to 6 are provided, depending on different criteria as following:

Suggested criteria	γ_m
Works carried out by experienced specialist contractor; tired and tested materials; materials; materials from consistent supply or mix; materials tested fully in accordance with provisions of Appendices A and B; full programme of compliance testing during construction; materials well within recommended limits of suitability criteria; material property test results demonstrate consistent repeatable performance	3.0 – 4.0
Works carried out by general contractor under supervision; untried material with limited laboratory test data; full programme of compliance testing during construction; materials within recommended limits of suitability criteria	4.0 – 5.0
Works carried out by inexperienced labour under some supervision; untried natural or quarry waste material with limited test data; limited programme of compliance testing; materials marginally comply with recommended limits of suitability criteria; material property test results show some inconsistency	5.0 – 6.0

Table E.4: Values for material partial safety factor (γ_m) (source : (Walker et al., 2005)*)*

Method found in French guides

Two technical documents, providing recommendations on methods of design to employ for rammed earth, can be found in France: the French guide of good practices (2019) and a book named “construire en pisé” edited by the French laboratory specialized in earth construction CRATerre.

Guide of good practices

The guide of good practices defines two compressive strength: the compressive strength just after fabrication of the wall, therefore at the manufacturing water content; and the compressive strength after the drying process have been completed. The guide recommends to consider the compressive strength at the manufacturing water content ("Guide des bonnes pratiques de la construction en terre crue," 2018, p. 19), for which a generic value of 0.2 MPa is proposed. However, in case of doubts on the resistance of a specific earth or if building's project is subjected to higher loads than for small buildings of one storey, the guide proposes an approach to assess the compressive strength.

For this, an appendix is proposed to obtain the design compressive strength from testing, including different recommendations:

- Implementation of the specimens in similar conditions than the on-site
- Testing should be done in the condition of the highest water content the wall on-site will be subjected
- Aspect ratio between 2 and 2.5
- Slow loading and "implementation of an anti-fretting system"
- Take into account a shape factor: apply a safety factor of 3 in case of cylinders, 5 in the case of prisms
- Test 3 specimens with a variation lower than 10% and select the lowest value for the design.

No more recommendation is provided in the manufacturing of specimens which was one of the topics of the Chapter 1.

Book recommendations

Another guide[174] has been published in France on rammed earth building's design, however this guide is not as consensual among professionals as it is for the GDBP.

Compared to the GDBP, in this book, no precision are first provided on which compressive strength should be considered between the one before or after the drying process. However, in the appendix associated to the recommendations to follow to test the material it can be read:

> *« This appendix describes the test allowing to assess, **on dried specimens**, the compressive strength of rammed earth" p107*

[174] CRATerre, 2020, Construire en pisé, Editions du Moniteur, 148 pages

Moreover, the conditions in which laboratory testing are required are not specified. The book defines the compressive strength as follow (p31):

$$Rcd = \frac{Rck}{\gamma_M}$$

Where Rcd is the design compressive strength, Rck the characteristic compressive strength and γ_M the safety factor equal to 5.

The characteristic compressive strength here is considered as the mean value on 5 specimens tested.

The recommendations provided on the compressive strength testing preparation highlights the relevance of the results obtained in Chapter 1. Indeed, the author recommend to manufacture the specimens with an earth sieved at 20mm, and the same manufacturing water content than the one used for the implementation of rammed earth. By doing so, they don't consider the equivalent parameters proposed in chapter 1, which potentially lead to wrong results in the case of earth composed of big grains.