Rediscovering of vernacular adaptative construction strategies for sustainable modern building : application to cob and rammed earth

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Rediscovering of vernacular adaptive construction strategies for sustainable modern building - Application to Cob and Rammed Earth

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Redécouverte des stratégies d'adaptation constructive vernaculaires pour la construction durable contemporaine – application à la bauge et au pisé

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Abstract

The use of local, natural and unprocessed materials offers promising low impact building solutions. The wide spatial variability of these materials is, however, an obstacle to a large-scale use. The construction strategies developed by past builders were dictated by the local climate and the quality and the amount of locally available construction materials. These construction strategies can be regarded as an optimized management of local, natural and variable resources and are a source of inspiration for modern sustainable building. Unfortunately, this knowledge was lost in Western countries during the 20th century. Vernacular earth construction know-how rediscovering requires the development of rational built heritage investigation means. Another issue regarding the use of natural and variable building material is their compliance with modern building regulation. The development of performance based testing procedures is proposed as a solution to facilitate the use of earth as a building material.

A multidisciplinary approach is proposed, combining micromorphology, pedology, geotechnics and heritage disciplines to study vernacular earth heritage. It provides complementary tools to assess pedological sources of construction material and geotechnical characteristics of earth employed in vernacular earth heritage. It also provides a detailed description of the construction process of vernacular earth heritage. Using these results, it was possible to draw resource maps and provide a scale of magnitude of resource availability at regional scale. Two performance based testing procedures were proposed in order to take into account the natural variability of earth in a modern building context.

Earth construction will play an important role in the modern sustainable building of the 21st century if the actors of the sector adopt earth construction processes able to meet social demand, with low environmental impact and at an affordable cost. The study of earth heritage demonstrated the ability of historical earth builders to innovate in order to comply with social demand variations and technical developments. Earth construction benefits of an old and rich past and it would be a non-sense to leave this past behind. The analysis of earth heritage and the rediscovering of vernacular construction techniques is a valuable source of inspiration for modern earth construction. The valorisation of vernacular knowledge will save time, energy and avoid repeating past mistakes. The future of earth construction should be a continuation of past vernacular earth construction.

Keywords

Rammed earth; cob, micromorphology; pedology; vernacular heritage; earth construction; sustainable modern building

Résumé

L'utilisation de matériaux locaux, naturels et non transformés offre des solutions prometteuses de construction à faible impact environnemental. La grande variabilité spatiale de ces matériaux est cependant un obstacle à une utilisation à plus grande échelle. Les stratégies de construction développées par les anciens bâtisseurs ont été dictées par le climat local et la qualité ainsi que la quantité de matériaux de construction disponibles localement. Ces stratégies de construction peuvent être considérées comme une gestion optimisée des ressources locales, naturelles et variables et sont une source d'inspiration pour la construction durable moderne. Malheureusement, cette connaissance a été perdue dans les pays occidentaux au cours du 20ème siècle. La redécouverte des savoir-faire traditionnels requiert le développement de moyens rationnels d'analyse du patrimoine. Un autre problème concernant l'utilisation de matériaux de construction naturels et variables est leur conformité vis-à-vis de la réglementation du secteur du bâtiment. Le développement de procédures d'essais performantiels est proposé comme solution pour faciliter l'utilisation des techniques de construction en terre.

Une approche multidisciplinaire est proposée, combinant micromorphologie, pédologie, géotechnique et étude du patrimoine pour analyser le bâti vernaculaire en terre. Cette approche fournit des outils complémentaires pour évaluer la source des matériaux de construction et identifier les caractéristiques géotechniques de la terre employées dans le patrimoine. Il fournit également une description détaillée des processus vernaculaires de construction. En utilisant ces résultats, il a été possible d'élaborer des cartes de ressources et d'estimer l'ordre de grandeur de la disponibilité des ressources à l'échelle d'une région. Deux procédures d'essais performantiels ont été proposées afin de tenir compte de la variabilité naturelle des terres dans le contexte réglementaire actuel.

La construction en terre jouera un rôle important dans la construction durable du 21ème siècle si les acteurs du secteur adoptent des procédés de construction capables de répondre à la demande sociale, avec un faible impact environnemental et à un coût abordable. L'étude du patrimoine en terre a démontré la capacité des anciens bâtisseurs à innover afin de se conformer aux variations de la demande sociale et aux développements techniques. La construction en terre bénéficie d'un passé ancien et riche et il convient de tirer profit de ce retour d'expérience. L'analyse du patrimoine en terre et la redécouverte des techniques de construction vernaculaire est une source d'inspiration précieuse pour la construction contemporaine. La valorisation des connaissances vernaculaires permettra d'économiser du temps, de l'énergie et d'éviter de répéter les erreurs passées. L'avenir de la construction de la terre doit s'inscrire dans la continuité de la construction en terre vernaculaire.

Mots Clés

Pisé; bauge; micromorphologie; pédologie; patrimoine vernaculaire; construction en terre; construction durable

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Chapter 1 Introduction

1.1 Earth, a sustainable material for construction

1.1.1 Resource management

In the Western countries, the construction sector consumes a large volume of natural resources [1–6] and is responsible for about 50 % of wastes production in the European Union [2,3,7–11]. These wastes have a negative environmental impact [8–10] and it is increasingly difficult to find suitable landfill areas [10,11]. The political demand thus promotes waste recycling [8,10,11], circular economy [8] and encourages producers to find a market for construction wastes. In this context earth construction provides a relevant option.

If unstabilized, reversible clay binding allows a complete and low-energy reuse of earth at end of life [12–19]. The unstabilized earth construction allows an almost infinite reuse of the material for construction or its return to agricultural land. The material resource for earth construction is deemed to be huge, and the impact of earth excavation in term of land occupation low [20]. Nonetheless, earth is a non-renewable material and its consumption has to be properly managed.

The specifically excavation of earth for construction more specifically concerned historical buildings. Nowadays, among the large amount of wastes produced by the building sector, about 75 % are soils and stones [7,21]. These wastes provide a huge amount of resource for earth construction, considering the little need of current modern earth construction sector in Western countries. To turn current earth material volume needs into a credible market for earthwork wastes, earth construction sector has to significantly grow.

Considering that materials for earth construction are wastes of the construction sector and that unstabilized earth material is endlessly reusable, earth can be regarded as one of the load-bearing construction material that best meet the challenges of circular economy.

1.1.2 Energy

Embodied energy together with operational energy of the building sector represent approximately 40 % of global energy use [2,3,5,22,23]. As a consequence, the building sector is a major producer of greenhouse gases that contribute to climate change [3–5,12,22]. Until the 2000s, only operational energy was considered because of its dominant share in the total life cycle. Since then, the use of more efficient equipment and insulations modified the balance between embodied energy and operational energy so that the proportion of embodied energy increased [3,5,24]. In order to pursue energy saving effort, the next challenge for the building sector will be the reduction of embodied energy [5]. This involves good maintenance of existing buildings and the use of construction materials with low embodied energy [25–27].

Historical builders mainly had animal energy and unprocessed local materials for construction purpose. As a consequence, embodied energy of earth heritage is almost zero. Nowadays, in Western countries, excavations are carried out using mechanical diggers. On-site, earth dug from building foundations or from landscaping is used for construction. When not enough earth is available on-site or if on-site earth is unsuitable for construction, the material can be supplied from earthwork sites near the building site. Afterwards, implementation is conducted using manual and/or mechanized means. The recourse to mechanized means and possible transportation of earth increases the embodied energy of buildings. However, the embodied energy of modern unstabilized earth construction remains very low in comparison to other materials conventionally used in construction [1,12,13,15,17–20,22,27–32]. For example, embodied energy of a wall made of earth is about 20 times less than this of a hollow cinder block wall [12,22,28]. As a consequence, earth construction is considered as a low greenhouse gas emitter [3,12,14,17,22,27].

This is not the case of stabilized earth construction. Indeed, even if stabilization could increase the durability of buildings, the stabilisation of thick earthen walls, even at low percentage, consume large amount of energy and prevent the reuse of the material at end of life [29,33].

Historic earthen buildings represent an important, although difficult to quantify, part of the human habitat worldwide. In France, according to Michel and Poudru [1], in 1987, there were approximately one million earthen houses (rammed earth, adobe and cob) with an average age of approximately 100 years and a minimum age of 50 years. Improving the durability of earth heritage will save as much energy as it would be required for new constructions [34]. The proper maintenance of these zero-embodied energy buildings is also a major challenge for limiting building sector energy consumption, and, as a consequence, its environmental impact.

1.1.3 Indoor comfort

Thanks to their high thermal mass [17,18,31,35–45], and their high hygroscopicity enabling water phase changes [45], earthen walls buffer outdoor temperature variations.

They are able to accumulate solar energy during the day and restitute this energy during the night [38,46]. These features provide to inhabitants of earthen buildings a good thermal comfort and more specifically during summer period.

Thanks to their high hygroscopicity, earthen materials are able to rapidly absorb a significant amount of water vapour and also to restitute water vapour in building indoor air. Indoor air quality is closely linked to relative humidity levels and therefore moisture buffering of earthen materials is beneficial for health and well-being of the occupants [4,12,14,17,22,31,32,41,43,47–51].

Some authors mention several other beneficial properties of earthen buildings such as: good acoustic properties [52,53], fireproof properties [23,53], non-toxic and non-allergic properties [4,23,29] and even a capacity to adsorb pollutant from the indoor air [29]. These features have however never been clearly demonstrated and require more scientific investigations to be stated.

1.1.4 Social impact

Earth is one of the first construction material employed by human and has been continuously employed since then. Earth meets human construction needs for more than 10,000 years [4] and left us an important and rich architectural heritage worldwide. For example, 20% of cultural sites of the UNESCO World Heritage List are fully or partially made of earth [54]. This heritage has high historical and social values and should be properly maintained. This implies the preservation of vernacular know-how. The local preservation and promotion of earth heritage and know-how are also important to assure the development of the local earth sector [27] as well as the development of the local touristic sector.

Earth construction requires an intensive workforce. In low-income countries, the workforce is inexpensive and, as a consequence, earth construction is cheaper than conventional construction [1] (by 60% in Nigeria for example [55]). In high-income countries workforce is expensive and earth construction more expensive than conventional construction [1]. These two situations are thus examined separately.

In low-income countries, there is a strong demand for affordable houses in high urbanization rate areas [55] as well as in remote areas [28]. Conventional construction requires the importation and the transportation of materials whereas the use of local materials, like earth, significantly reduces construction costs [28,55]. Furthermore, low-income countries benefit of a vibrant vernacular construction sector, providing sufficient skilled workforce. Earth construction has a high economic potential in low-income countries [1]. Nonetheless, earth, by opposition to steel reinforced concrete, is synonym of low economic status [28], which constrains the development of earth construction sector.

In high-income countries, earth construction sector also suffers from an archaic image. Indeed, the building sector is mainly adapted to industrial building materials. Education, engineering, design, regulations, insurance, none of the sectors of building industry take into consideration the use of non-conventional materials, which has for consequence to marginalised them [56,57]. Yet, earth construction could provide several social benefits in high-income countries. On earth building sites, implementation is carried out by skilled craftsmen whose expertise is recognized by other actors of the construction [2]. This increases their responsibility and thus contributes to the limitation of building defect risks. This also increases the esteem of mason's corporation and makes this profession more attractive to new mason generations. Since vernacular construction techniques depend on local conditions, the required skills to build with earth vary from a region to another. Earth construction thus creates jobs that cannot be relocated. Furthermore, earth material can be considered as free. The cost of earth construction is almost entirely due to salaries and social taxes. As a consequence, earth construction sector profits the local and social economy and has, therefore, a positive social impact.

1.1.5 Sustainability

If appropriately employed, earth construction offers many advantages in terms of resource management, environmental impact, indoor comfort and social impact. Earth has the potential to be one of the most sustainable construction materials. However, inappropriate architectural design, long distance transportation of material, steel bar reinforcement, high impact admixture addition or significant grading correction can deeply alter its sustainability. The sustainability argumentation proposed in section 1.1 for earth construction should be considered as an ultimate aim. However, each building site faces particular constraints and can hardly meet all sustainability goals in the same time. Unlike conventional building materials, which can be regarded as easy-to-use building solutions, earth construction demands a strong commitment of project owners and project managers. Therefore, the use of earth for construction should be justified by its beneficial effects. This is why earth construction goes hand in hand with sustainability assessment.

1.2 Vernacular earth construction processes, a source of inspiration for modern sustainable building

The first attested use of earth as a building material dates back to the Neolithic time [4]. Earth is one of the oldest building materials employed by mankind. Earth construction techniques have been employed empirically for centuries. The lessons learned by historical builders from successes and failures of their constructions allowed them to select the most suitable construction technique and architectural solution with regard to specific local conditions [29,31,56,58–62]. The construction strategies developed by past builders were dictated by the local climate and the quality and the amount of locally available construction materials. These resource and climate constraints, combined with inhabitant needs, engendered local construction cultures, changing over time. The late 19th and early 20th century examples of earth constructions, in the European countries, are the outcome of this evolution. Past builders mainly had animal energy and unprocessed local materials for construction purpose. These local construction cultures can be regarded as very low impact construction processes. Earth heritage is, therefore, a precious testimony of low impact construction and is a source of inspiration for modern sustainable building [58].

In Western countries, the introduction of industrial ready for use building materials at the beginning of the 20th century competed with traditional building materials. During the 20th century, the abundance of inexpensive fossil energy favoured industrial products at the expense of traditional ones. This evolution has relegated skilled craftsmen to the simple role of applicator of ready for use products, leading to the loss of vernacular know-how [27,31,59,61,63–65].

The context of the early 21st century is very different. Greenhouse gas emissions are responsible for a rapid climate change impacting all ecosystems. The consummation rate of fossil energies and resources is unsustainable. The incorporation of synthetic product in construction materials is a source of emission of volatile organic compounds that affect indoor air quality. The challenge of modern building construction will be to propose construction processes using renewable materials or materials reusable at end of life, consuming low embodied and operational energies and guaranteeing a good indoor air quality. The use of local non-conventional, traditional, natural materials, like earth, is one of the ways to move towards sustainable building.

Vernacular built heritage is a valuable and reliable source of information for modern sustainable building [61]. The combination of vernacular processes with the best practices of conventional building sector can make for significant innovation [57,60]. This back to natural materials is sometimes considered as a sign of backwardness. Nonetheless, this does not mean a return to the ways of our ancestors, but taking into consideration local conditions and materials together with current resident needs to propose sober and modern building solutions [56]. Indeed, men and women of the 21st century would not accept to live in the same earth houses than those of the Middle Age, just like men and women of Middle Age would not have accepted to live in Bronze Age earth houses. Actually, earth construction processes and architectural designs have adapted over the centuries to social demand. Rediscovering vernacular construction strategies will provide information on the way to optimize the use of local materials under local conditions and how these construction strategies have changed under the influence of social demand.

Earth heritage analyses almost entirely focus on architectural design, which is a major concern for earth buildings. However the relationship between the available local material and its associated process is also a major issue for earth construction, but very little data exists. The aim of this work is to rediscover vernacular earth construction processes and their associated material sources. To this end, scientific methods are developed in this work to analyse earth heritage in order to identify materials and processes employed by historical builders. This study more specifically focuses on rammed earth and cob techniques.

Another challenge to promote the use of local materials in modern construction is the natural variability of earth material. This variability makes the validation of non-conventional construction processes difficult in the current building regulation context. Indeed, the validation of construction materials is determined *a priori*. In the case of earth, it is not yet possible to assess *a priori* the compliance of the material with national regulations. A solution is to assess the compliance of specimens manufactured on-site and characterized directly on-site or in laboratory, using a performance based approach. This method allows validating earth elements regardless of the material employed. This requires the development of specific tests to assess the performance of earth elements. Two different performance-based procedures are proposed in this manuscript, one for plasters and another for cob walls.

1.3 Thesis layout

The manuscript is organised in 5 chapters. Chapter 1 presents the context (section 1.1) and the research question (section 1.2) of the study and also a brief description of vernacular earth construction processes (section 1.4). Chapter 2 discusses the identification of vernacular earth material. The definition of earth material (section 2.1) and the assessment of the suitability of earth for construction are discussed (section 2.2). The identification of vernacular earth material is assessed using micromorphology for a single building (section 2.3) and using the cross-referencing of soil and heritage database at regional scale (section 2.4). Chapter 3 deals with the description of vernacular earth construction processes. A brief rammed earth bibliography (section 3.2) and an extend cob bibliographical analysis (section 3.3) are proposed. Micromorphological analysis of a rammed earth (section 3.4) and a cob (section 3.5) building are presented. Chapter 4 debates the challenge of modern earth construction (section 4.1) and the performance based approach (section 4.2). It also proposes a performance based test for earth plaster (section 4.3) and for cob (section 4.4). Finally, chapter 5 draw the general conclusion of this work.

1.4 Vernacular earth construction processes

1.4.1 Definitions

To provide a definition of vernacular earth processes it is essential to understand what makes them different. Thus, before proposing definitions, the classification of vernacular earth construction techniques is to be considered.

Some earth construction process classifications were proposed in the literature but no general agreement exists [22,65–71]. To provide a general framework for this thesis, a new classification is proposed. Among existing classifications, those based on the distinction between wet methods and dry/compaction methods [22,65,70] are judged more appropriate for classification purpose. For wet processes, earth mixture is employed in a plastic state and mechanical strength of the material is provided through drying shrinkage densification (adobe, cob). For dry processes, earth mixture is employed at an optimum water content and mechanical strength is provided through compaction densification (Compressed Earth Block and rammed earth). A second distinction is made according to the implementation of the earth in the wall, either through masonry units (Compressed Earth Block and Adobe) or direct monolithic wall fabrication (cob and rammed earth).

These classifications were adapted and supplemented with non load-bearing techniques (wattle and daub and plasters) and a classification is proposed in Figure 1. This classification is based on three criteria: (1) water content of mixture (dry-compression densification/wet-shrinkage densification), (2) implementation type (dry masonry units built with a mortar/direct implementation of earth mixture with water content of manufacturing stage in order to build a monolithic wall/infilling of a timber frame structure/coating of walls/bricklaying) and (3) structural role of the earth element (load-bearing and freestanding walls/non load-bearing walls).

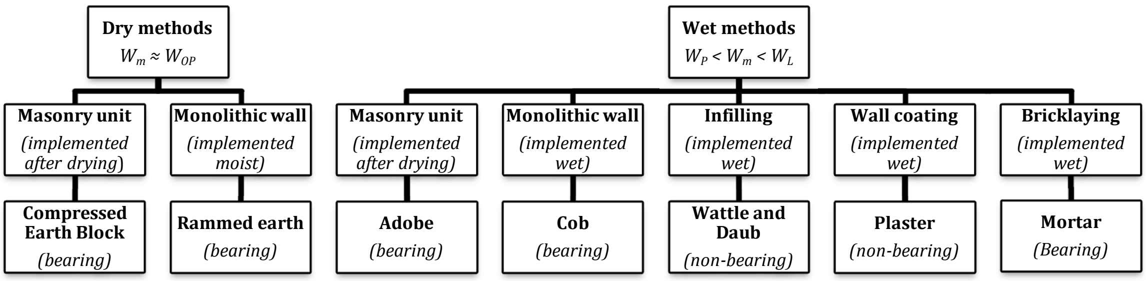


Figure 1. Earth construction processes classification, adapted after [22,65,70]. *The distinction is made between load-bearing and freestanding techniques (bearing) and non load-bearing techniques (non-bearing). (Wm = water content of manufacturing stage, WOP = optimum Proctor water content; WP = water content at plastic limit; WL = water content at liquid limit).*

Using this classification, it is possible to define earth construction processes. These definitions should be wide enough to comprise all process variations, but precise enough to differentiate a process from the others:

- Compressed Earth Blocks (CEB): masonry unit compacted at an optimum water content, dried and laid in order to build a load-bearing or freestanding wall.
- Rammed Earth: earth compacted at an optimum water content layers by layers inside a formwork in order to build a monolithic and load-bearing or freestanding wall.
- Adobe: masonry unit moulded at plastic state, dried and laid in order to build a load-bearing or freestanding wall.
- Cob: earth elements mixed in a plastic state, implemented wet, in order to build a monolithic and load-bearing or freestanding wall.
- Wattle and Daub: earth elements mixed with fibres in a plastic state, implemented wet, in order to fill a timber frame load-bearing structure.

- Plaster: earth mixture carried out at plastic state, implemented wet, in order to coat wall surfaces.
- Mortars: earth mixture carried out at plastic state, implemented wet, in order to lay bricks.

1.4.2 Proximity of earth construction processes with cob

Cob is one of the less studied earth construction process compared to rammed earth and adobe for example. However large process variations are attested for cob technique (section 3.3) and some of them present similarities to other earth construction techniques. These similarities shed a new light on the proximity of earth construction processes and are discussed in this section.

Compressed Earth Block technique is quite dissimilar from cob. On the contrary, adobe, wattle and daub, rammed earth, and plasters do have similarities with cob. Rammed earth differs from cob since it is a dry technique requiring a compactive effort [72,73]. A confusion comes from the use of shuttering for both rammed earth and shuttered cob [65,74]. For rammed earth, shuttering are employed to make the ramming process efficient, whereas, for shuttered cob, shuttering are employed to avoid the trimming of the faces of the wall and therefore accelerate the wall faces rectification stage [65,72].

Wattle and daub, plasters, mortars and adobe mixtures are prepared in a similar way to wet cob mixture [75]. However, maximum particle size diameter is higher for cob mixture than for wattle and daub, plasters, mortars and adobe mixtures [22].

Wattle and daub is quite different from cob since earth is infilled in a timber frame and do not play any structural role [76] as well as plasters that are overlaid on wall face. Nonetheless, it should be pointed out that some authors mentioned the use of both cob and wattle and daub inside the same building [77,78].

Adobe and the cob process variations that consist of stacking cut or modelled plastic elements (case b and c, section 3.3.3.1) are quite similar, but adobes are implemented dry and require to be grouted with a mortar, whereas cob elements are implemented damp without mortar [76,77]. It should be noted that some authors mentioned the use of both cob and adobe inside the same building, or next to each other [22,79], or together with an alternation of courses of adobe and cob [80].

Proximities between cob and other earth construction processes can be drawn at mixture and implementation stages (Figure 2). This proximity can be the result of mutual technical exchanges and/or shared past of earth construction processes. There is a link between earth construction processes and cob can be regarded as a link between adobe and rammed earth (Figure 2). A similar continuity can be drawn between adobe and Compressed Earth Blocks [70]. These similarities highlight a general continuity between all earth construction techniques. Earth construction techniques should be considered as a whole, and not as separated processes.

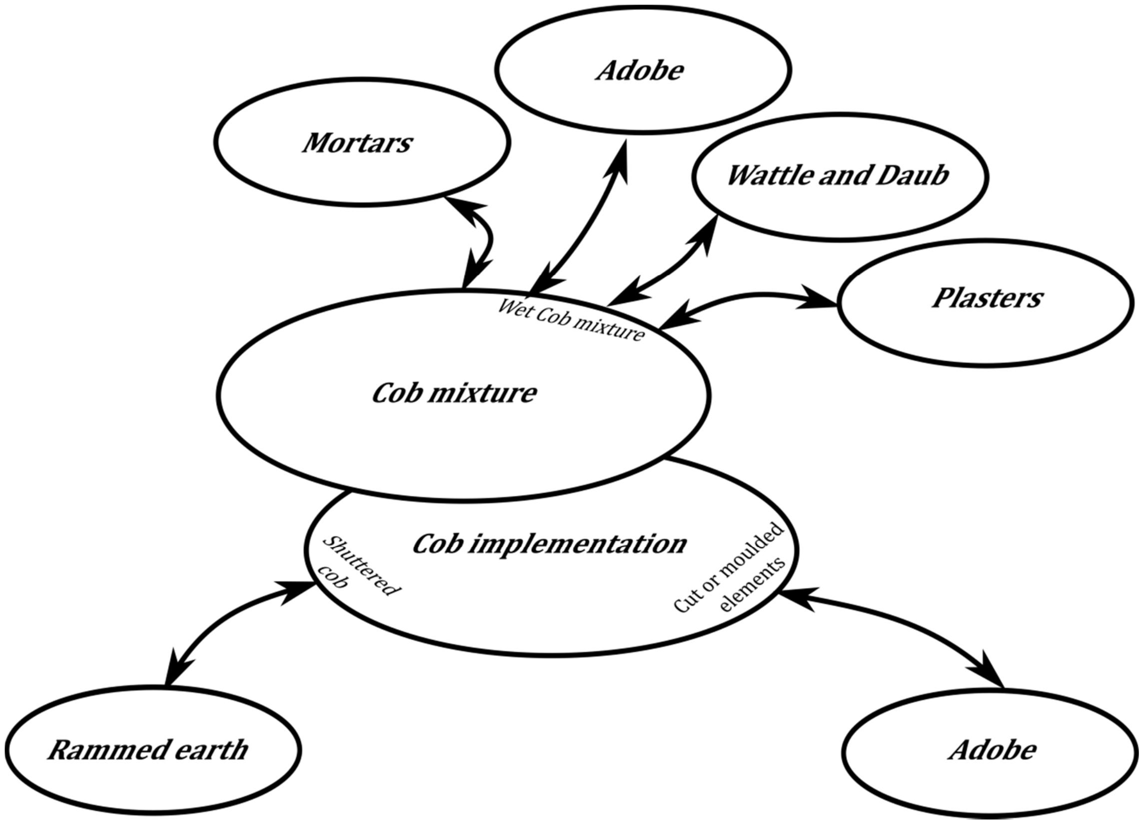


Figure 2. Cob process stages and related earth construction processes.

Chapter 2 Identification and quantification of vernacular earth construction material

2.1 Definition of earth material

2.1.1 Introduction

In the literature, authors agreed on the origin of materials employed for earth construction. They are excavated from local soil and have a minimum clay content and very little to no organic matter [22,81–89]. However, few authors provide specific information on pedological or geological origin for these materials. According to authors, earth materials could have been excavated from a soil horizon [1,90–92], from an alterite [93] and/or from a soft rock deposit [87,90].

Material source suitable for earth construction concern all soft materials available on Earth surface, i.e. “soil” in its Geotechnical definition. These materials are produced by geological, weathering and pedological processes. The study of these materials concerns geology, geomorphology, pedology, agronomy and geotechnics. The frontiers between these disciplines are not clear and the terms and definitions used are different, sometimes inconsistent, and finally confusing [89,94,95]. The aim of this section is to clarify terms and definitions necessary to provide a precise description of earth construction material. A list of definitions is also proposed in Appendix A.

2.1.2 Weathering

The lithosphere is constituted of rocks formed by long time scale geologic processes, i.e. magmatic, sedimentary and metamorphic processes. Most of the geological formations are made of hard rocks and cannot be used for earth construction. Nonetheless, sedimentary deposits not affected by diagenesis (marls, clays) provide loose materials potentially appropriate for earth construction.

When exposed to the surface, the physicochemical equilibrium of rocks is in imbalance with their new environment, and rocks are exposed to weathering [92,96]. Weathering can be decomposed in *mechanical weathering* and in *chemical weathering.*

Rocks are not homogeneous and are affected by discontinuities, cracks and faults. These heterogeneities favoured mechanical weathering processes [97]: (1) the volumetric change of liquid water to ice under freezing, *frost weathering*, is a strong rock disintegration factor; (2) the removal of large quantities of materials by erosion above rocks modifies the mechanical equilibrium and generates unloading cracks, parallel to soil surface; (3) cracks enlargement is favoured by plant root growing; (4) day/night temperature variations, *thermal weathering*, produce dilatation/shrinkage cycles that generate cracks; (5) the crystallisation of secondary minerals in pores or microcracks of rocks, *salt weathering,* for example, contribute to rock fragmentation.

Mechanical weathering do not affect the chemical composition of rocks, but increases the contact surface between water or air and rocks, allowing and amplifying chemical weathering [97].

Rain water pH can be regarded as neutral, but the dissolution of carbon dioxide of the atmosphere, or produced by biological activity in soils, modify the dissociation equilibrium in favour of H^+. Under acid conditions, minerals are prone to dissolution. This dissolution concerns a leached layer at the mineral surface [98,99]. Two separated processes operate simultaneously in the leached layer: (1) the substitution of cations from the mineral (K^+, Na^+, Ca^{2+}, Mg^{2+}) with excess protons of leached layer, and (2) chemical hydrolysis reactions releasing Si and O into the bulk solution [97–99]. Chemical weathering rate differs from a mineral to another [97,100,101].

Chemical weathering releases chemical elements that are useful for plants, lichens, fungi and bacteria living in the soil. Biologic activity of these living organisms are able to intensify the chemical weathering of minerals, thanks to organic molecules, in order to extract inorganic nutrients [102]. The weathering action of organic molecules involves several oxidoreduction reactions and the production of weathering agents, such as organic acids and chelating molecules [97,102].

Chemical weathering leads to the dissolution of minerals by ion leaching. Dissolution is congruent if it affects all mineral ions on a similar manner. In this case, mineral crystalline structure disappears, leaving a void having a crystal habit shape [97,101,103]. Dissolution is incongruent if it only affects some mineral ions. In this case, the unweathered solid phase is altered to another solid phase, forming a secondary mineral [97,101]. Leached ions, transported across cracks and voids, can generate neoformed minerals [97].

The effect of weathering tends to decrease from land surface downward to the unweathered bedrock, creating a weathering profile, also named “weathered mantle”, “alterite”, “weathered bedrock” or “saprolith” [94,103–107]. Weathering profile is divided into several rock weathering grades [94]: a lower level in which the original petrographic texture is maintained and still recognizable, named Isalterite, and an upper level in which the original textural features have partly or totally disappeared, named Alloterite [103]. It could also be divided into a lower level containing less than 20% altered minerals, named Saprock, and an upper containing more than 20% altered minerals, named Saprolite [92,104,106,108] (Figure 3).

Weathering generates loose materials that are easily mobilized by ablation processes, i.e. colluvial, alluvial, eolian and glacial processes, to form superficial deposits [97]. Superficial deposits differ from soil since they have a dynamic history (erosion, transport and deposition), whereas soils formed in situ during stability episodes [109]. Nonetheless, when superficial deposits remain stable over time they are affected by weathering and pedogenic processes.

2.1.3 Soil formation

Soil formation, or pedogenic processes, over time, tend toward the complete transformation of a parent material into more stable components and structures [96,110]. This transformation depends on (1) mineralogical composition and structure of parent material; (2) climate, governing chemical weathering conditions; (3) soil living organisms, affecting chemical weathering to their profit; (4) relief, controlling horizontal transfers in soils; and (5) time, since an old soil will be more mature than a young one [96,102,105,110,111].

Soil is an accumulation of parent material weathering products and biota degradation products [96,110]. A fraction of these products are colloids (clays and humus) and are responsible for swelling and shrinking of soil by a change in moisture content. The repeated volumetric changes induced by seasonal moisture variations create vertical soil structural units, known as peds [96,112]. Peds facilitate the downward movement of water and colloids inside soil and the differentiation of soil in pedological horizons (Figure 3). Soil formation is a 3-dimensions balance among gains, losses, internal redistribution, and chemical and physical changes [96].

The alterite structure is inherited from bedrock whereas the soil structure characterized by soil horizons and peds results from pedogenic processes that erased the geological structure of parental material [97,110,113]. This change in structure allows differentiating soil from alterite. A vertical cross-section of weathered materials from ground surface to unweathered bedrock, according to several disciplines definitions [94,95,97,103,104,106,109,114] is proposed in Figure 3.

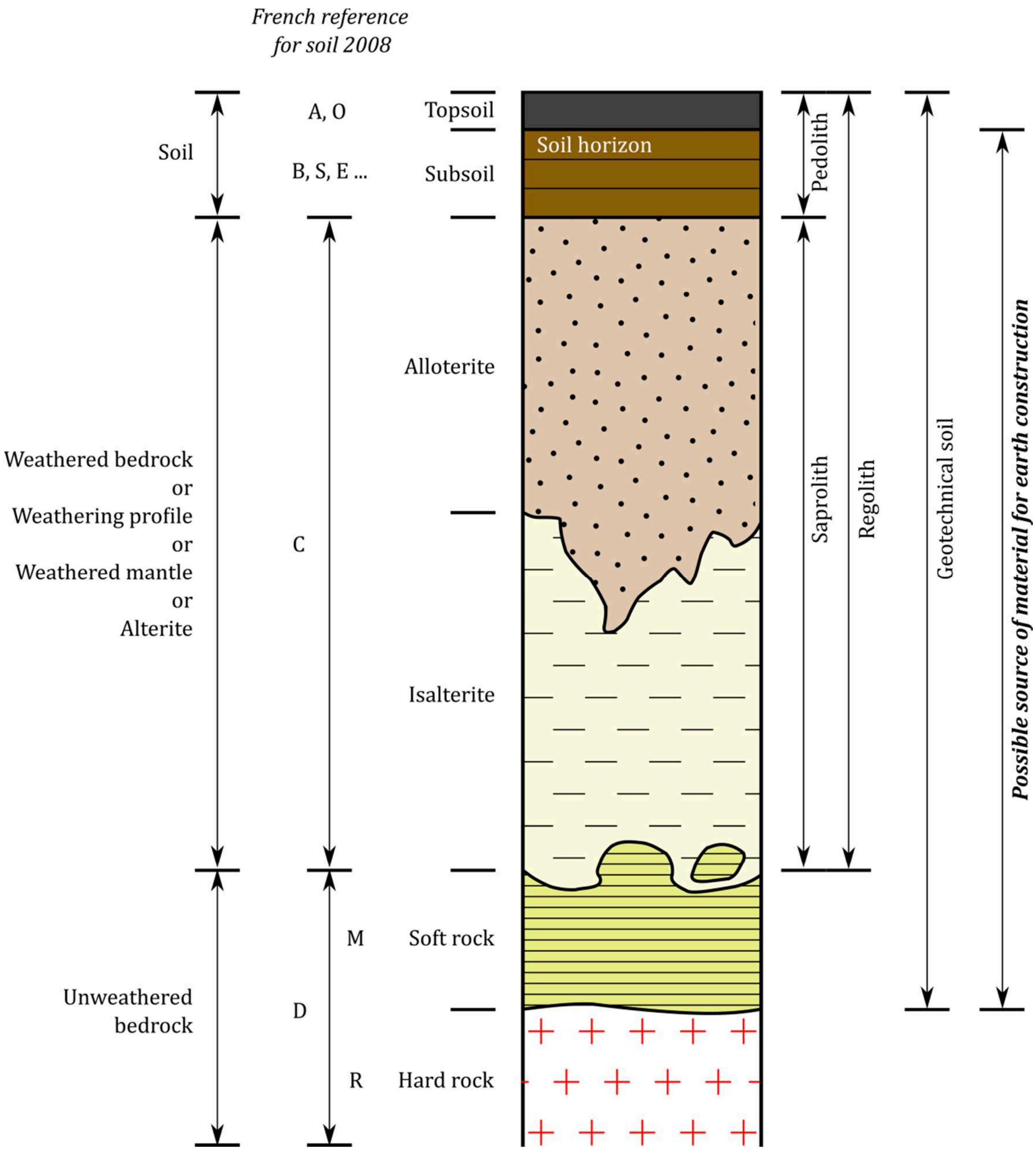


Figure 3. Vertical cross-section of weathered materials from ground surface to unweathered bedrock, according to several disciplines definitions.

Spatial variation of natural in-situ materials is often considered in two dimensions without regard to their vertical variability. In the literature, earth traditionally employed were identified as deriving from soft rock deposits [87], alterite [90,115] or subsoil [90,115] (Figure 3). Geotechnical definition of soil, excluding topsoil layer, offers the best description of the possible source of material for earth construction (Figure 3). Nonetheless, this definition encompasses materials with very different time-scale, spatial-scale and formation processes and no cartographic information exist for geotechnical soils. Geological maps provide information on soft rock deposits, if any, and sometimes on alterite. Soil maps provide information on topsoil and subsoil materials. Depending on the source of material, rock, alterite or soil, geological or soil map should be considered.

2.2 Assessing the suitability of earth for construction

Thanks to the legacy of previous builders and their own experience, past builders had a specific knowledge of the way to choose earth for construction [22,116,117]. Since this knowledge was orally transmitted and used senses such as touch, sight, smell, taste and hearing, it required a long learning alongside a master [116,118]. This knowledge is nowadays lost in the West, and different approaches are proposed for the assessment of earth suitability in the context of the modern building.

Suitability of earth for construction purpose can be determined thanks to a geotechnical approach, aiming at enhancing the mechanical strength of earthen specimens performed in the laboratory [82,83,119]. The most cited criterion to assess earth suitability is texture, i.e. balance between clay, silt, sand and gravel content [84]. Voids ratio is minimized in order to increase the contact between soil particles according to Fuller formula [82,86]. Consequently, grading envelopes adjusted to each earth construction technique were proposed in the literature [13,22,61,82,120–122]. However, the texture of earth collected in vernacular earth heritage buildings does not fit inside those grading envelopes [87,91,93,115,123,124]. Thus, grading envelopes available in the literature failed to give a full account of the diversity of earth traditionally employed in vernacular architecture.

Another approach to assess material suitability for construction is to analyse materials traditionally used in heritage buildings [91,93,115,123]. Indeed, the still existing earth vernacular heritage demonstrates the longevity of these constructions and therefore the suitability of earth traditionally employed by past masons. Soils for earth construction were excavated directly on-site or in a distance less than 1 km away from the building site [12,91,115,125–127]. As a consequence, the presence of earth heritage highlights the presence of soils suitable for earth construction [91,115]. Several authors identified the material source through comparison between materials inside walls of heritage buildings and available local materials thanks to geological analysis [87,91,93,123,127] and more rarely thanks to pedological analysis [91,115].

The latter approach, aiming at rediscovering vernacular knowledge, is employed in this section in two different ways. In section 2.3, the source of earth is identified at building scale thanks to micromorphological analysis for a rammed earth farm. In section 2.4 the source of earth is identified for cob at regional scale thanks to cross-referencing of heritage and soil databases.

2.3 Identification of material source for a building thanks to micromorphology – application to a rammed earth farm

2.3.1 Introduction

Micromorphology derives from pedology science [128]. It has been first employed in geoarcheology to study sedimentary sequences exposed by archaeological excavations before to be used for archaeological architectural remains investigation [129,130]. For archaeological building materials, micromorphology studies give access to features resulting from mechanisms that can reveal the elementary steps of the construction process [131–133] and also to features inherited from the in-situ soil. By comparing pedofeatures inherited from in-situ soil to pedofeatures of existing soils nearby the construction, it is possible to identify the soil horizon excavated for construction purpose.

To our knowledge, micromorphology was rarely used to characterize building materials, outside the archaeological context. [134] used this method to describe the petrography of an earth material, but they do not describe or study samples pedofeatures. The use of micromorphological investigation methods, for a 19th century rammed earth building is an original approach.

2.3.2 Materials and methods

2.3.2.1 Studied area

Renovation works performed in a residential building of a rammed earth farm, located in *Bresse* region, in *Cras-sur-Reyssouze* town (north of Lyon, France, see Figure 4), gave us the opportunity to collect rammed earth specimens of a well preserved inside wall. Specimens were sampled during the demolition of the wall. This wall was 5 m long, 4.7 m high and 0.5 m wide. As reported by a local source, the building dates back to 1860.

Topographical, geological and pedological contexts provide information about the soils surrounding the farm (Figure 5 and Figure 6). The farm is located on an alluvial terrace which is, topographically, above the Reyssouze valley, to the west, and below the Balvay plateau, to the east (Figure 6). According to geological map [135], the farm is located on sprayings of siliceous broken stones, remains of a Riss fluvioglacial deposit, overlying a Plio-Quaternary geologic formation, called "*Marnes de Bresse*" (Figure 6). [136] and [137] proposed a description of common soils of Bresse region, called toposequence, based on pedological surveys performed on 4 towns (Figure 6). Since the farm is located on a plateau, the local soil should correspond to a soil located on a high topography of the toposequence, i.e. clayey sandy-silt soil with iron and manganese spots (1-2, Figure 6) or silty clay to clayey silt soils lying on marls (3, Figure 6). In order to specify the pedological environment of the farm, a field survey was carried out.

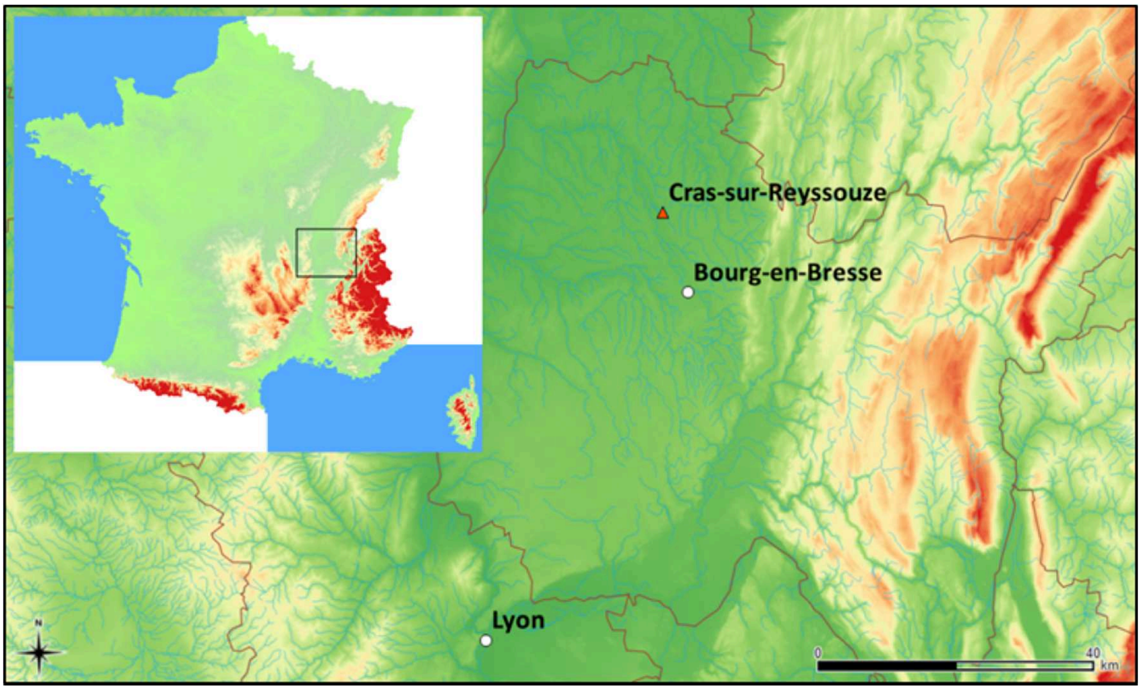


Figure 4. Location map of the rammed earth farm (Cras-sur-Reyssouze, France).

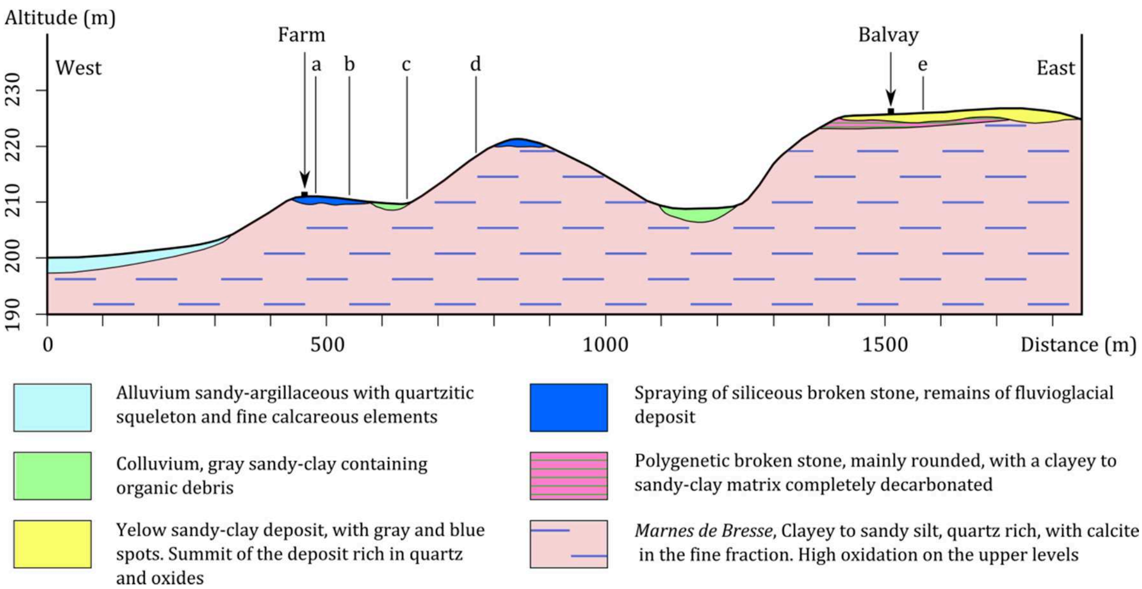


Figure 5. Geological East-West cross section of the surroundings of the rammed earth farm performed according to the geological map (Bergerat and Fleury 1985). Positions of pedological surveys are indicated (a, b, c, d and e).

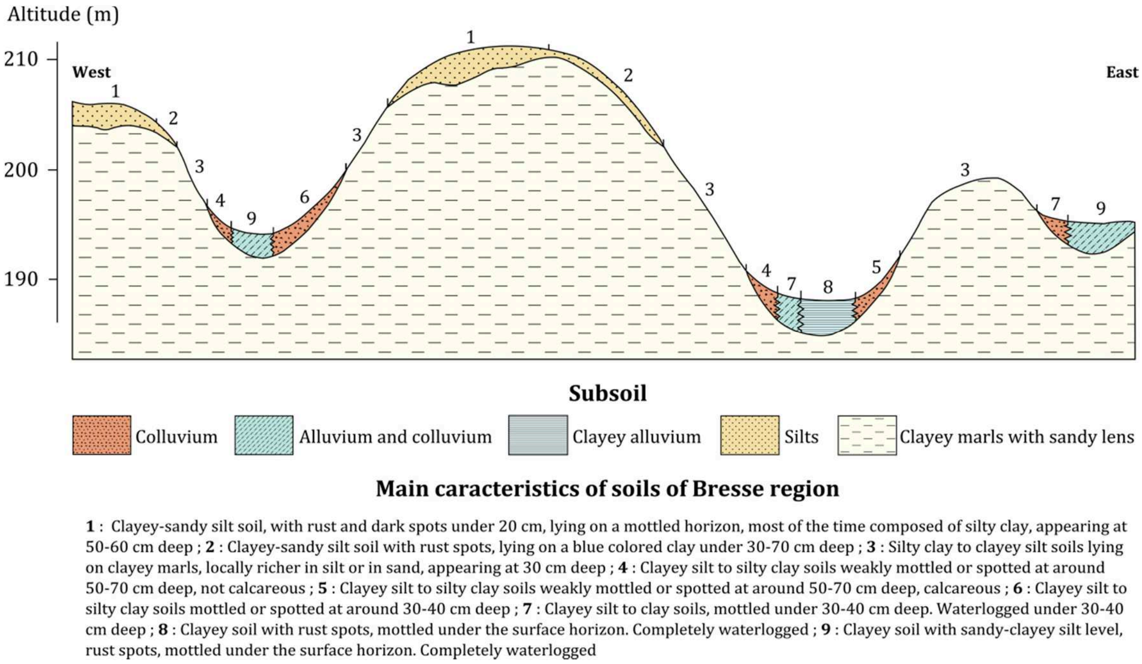
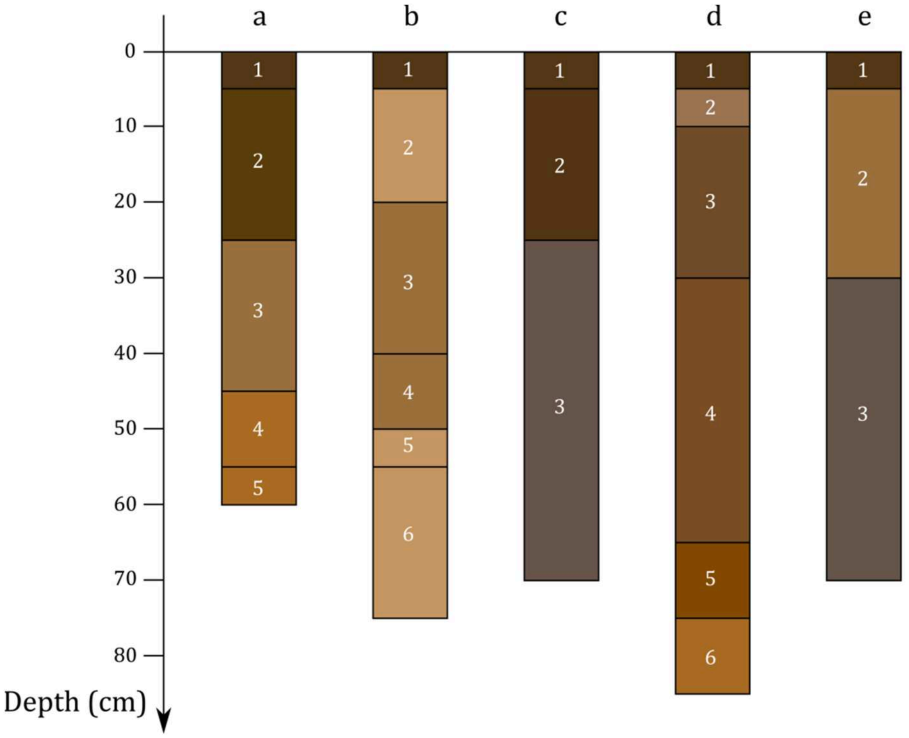


Figure 6. Summarized cross section presenting common soils of the toposequence proposed by [136]*and* [137].

2.3.2.2 Pedological surveys

The variability of "*Marnes de Bresse*" geological formation [135] combined with their large cartographic scale made it necessary to carry out a field study. In order to recognize the soils developed on the different geological formations and on the different topographical positions surrounding the rammed earth farm, and therefore to identify the potential material sources, five hand auger surveys have been performed along an east-west transect, between the farm and the Balvay village. These surveys are named *a* to *e* and presented in Figure 5. Their description is provided in Figure 7.



a - 1: surface horizon, rich in roots, under a grassland ; 2 : sandy silt ; 3 : clayey-sandy silt, friable, with rust impregnations ; 4 : sandy-clayey silt, with bright aspect and red spots ; 5 : mottled sandy-clayey silt with spots and ferromanganese nodules.
b - 1 : surface horizon, rich in roots, under grassland ; 2 : alternations of gray and yellow to orange levels, similar to those of horizon 6 ; 3 : sandy silt with some impregnations and some ferromanganese nodules ; 4 : same as 3 but more clayey ; 5 : same as 4, more spotted and richer in nodules ; 6 : sandy-clayey silt with dark and red spots and white zones. Richer in clay than horizon 5.
c - 1 : surface horizon, rich in roots, under grassland ; 2 : silty clay with thin roots ; 3 : mottled silty clay with gray dominant color. Abundant ferromanganese impregnations and coals.
d - 1 : surface horizon, rich in roots, under grassland ; 2 : fine gray sand with roots ; 3 : sand more yel--low and clearer than horizon 2 ; 4 : clayey sand more yellow than horizon 3 with ferromanganese impegnations ; 5 : clayey sand with coals ; 6 : mottled clayey-silty sand, clearer than horizon 5.
e - 1 : surface horizon, rich in roots, under grassland ; 2 : clayey-sandy silt (with fine sand), gradually richer in clay to the bottom, with some rounded pebbles, some ferromanganses impregnations and few millimetric coals ; 3 : gray mottled silty clay with centimetric ferromanganese impregnations.

Figure 7. Description of pedological surveys performed between the rammed earth farm and the Balvay village, locations are presented in Figure 5.

2.3.2.3 Wall specimens sampling and thin sections production

It was not possible to distinguish to the naked eye neither layers nor lifts of the rammed earth wall in which the samples were collected. Therefore, the sampling location was randomly selected. For this first study it was decided to do a limited horizontal section (CRA1 and CRA2, Figure 8) and a limited vertical section of the wall (CRA3 and CRA4, Figure 8). Since glass slides used for thin sections are 6.5 cm wide, 13.5 cm long and the thickness of the sample must be large enough to perform several cuttings, in the case of failure, the dimensions of the collected sample were 5×12×10 cm. Samples were carved by a craftsman thanks to an angle grinder (Figure 8). Samples were wrapped in towel paper and firmly maintained with tape to strengthen them. Then, position and orientation with respect to the face of the wall were labelled on samples.

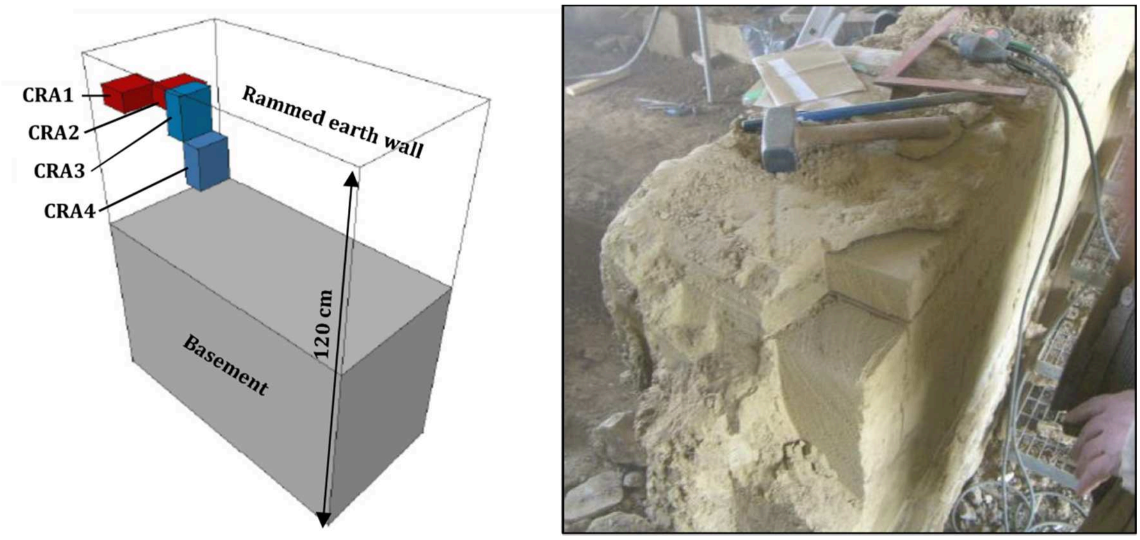


Figure 8. 3-dimension drawing of the 4 specimens sampling performed in the rammed earth wall (on left) and picture of the wall after sampling (on right).

Samples were air dried and then oven dried at 45°C. This temperature minimizes the changes in the mineral structure of the clay and the organic matter of the material. Afterwards, according to [138], samples were soaked with synthetic resin. After a one or two month's polymerization, a slab of the sample was cut. This slab was temporarily glued to a glass slide. The unattached face of the slab was levelled, grinded and glued definitively on a glass slide. The temporary glass slide was removed and the specimen was ground up to 25 µm, reference thickness for micromorphological analysis and for which the transparent observation of the thin section is possible, under plane polarized light (PPL) or crossed polarized light (XPL) [139]. Finally, a thin glass slide was glued on the second face to protect the thin section.

Samples collected in the wall were prepared in order to carry out 2 cross sections, the first one with samples CRA 1 and CRA 2 and the second one with samples CRA 3t, CRA 3d, CRA 4t, CRA 4d (Figure 8). A total of 6 thin sections were studied.

Thin sections descriptions were performed according to [140] and [139] with the help of [141] and [103]. The abundance of components was evaluated with an abundance charts [140,142]. These references provide a system of analysis and description of soil thin sections. The term *groundmass* refers to the nature, the shape and the distribution of components; *microstructure* refers to the spatial arrangement of mineral particles and of voids; *fabric* refers to preferential orientations of particles; *inclusions* refers to sporadic elements; and *limits* refers to soil discontinuities.

2.3.3 Results of thin sections description

2.3.3.1 Groundmass

The material of the groundmass consists of iron oxides rich silty-clayey fine fraction (Figure 9b) and a sub-millimetre sand fraction (40%) (Figure 9a). Sand particles are evenly distributed inside the micromass. Sand is almost exclusively composed of subangular to subrounded quartz, with regular surfaces. Finely fragmented vegetal remains, mostly roots, are also observed (Figure 9c). However, we note the presence of rare micas. The fine fraction is slightly birefringent.

2.3.3.2 Microstructure

At thin section scale, the material is constituted of subhorizontal units. The microstructure is quite dense with voids preferentially distributed inside horizontal units, creating an alternation of layers with greater and smaller porosity. Voids are unconnected and their faces are unaccommodated. They are distributed in the groundmass or linked to inclusions (clayey aggregates, ferromanganic nodules, biologic remains). The maximal observed diameter of voids is of the order of a millimetre.

A portion of the porosity (porosity of type 1) is constituted of channel voids. Some of these voids contain irregular aggregates, vegetal remains and/or Enchytraeids excrements (Figure 9d). Another portion of the porosity (porosity of type 2) has slightly rough walls of polyconcave, elongated or irregular shape. It does not contain aggregates or vegetal debris (Figure 9e). In the microstructure, cavities are frequently aligned and/or flattened along horizontal, tilted or vertical axes (Figure 9f and 8g).

2.3.3.3 Fabric

From thin section analysis, two main fabrics can be distinguished: Fabric 1, the most represented fabric, on which the sand fraction is randomly distributed inside the clayey-silty fine micromass (Figure 9a); and Fabric 2: locally, sand particles are organised along horizontal, tilted or vertical discontinuous lines (Figure 9h and 8i) and often associated with cavities alignments.

2.3.3.4 Inclusions

From thin section observation, the following inclusions, sorted by abundance decreasing order, can be reported: (1) Ferruginous nodules, generally with sharp shape (size ranging from 0.3 to 10 mm) (Figure 9j and 8k); (2) multi-millimetric silty-clayey aggregates (2-5% sand) with texture finer than the one of the groundmass, often associated with cracks on their edge (Figure 9l); (3) some multi-millimetric charcoals (Figure 9m); (4) rare multi-millimetric siliceous elements; (5) rare millimetric calcareous elements; and (6) rare millimetric fired earth pieces. These inclusions are randomly distributed inside the groundmass.

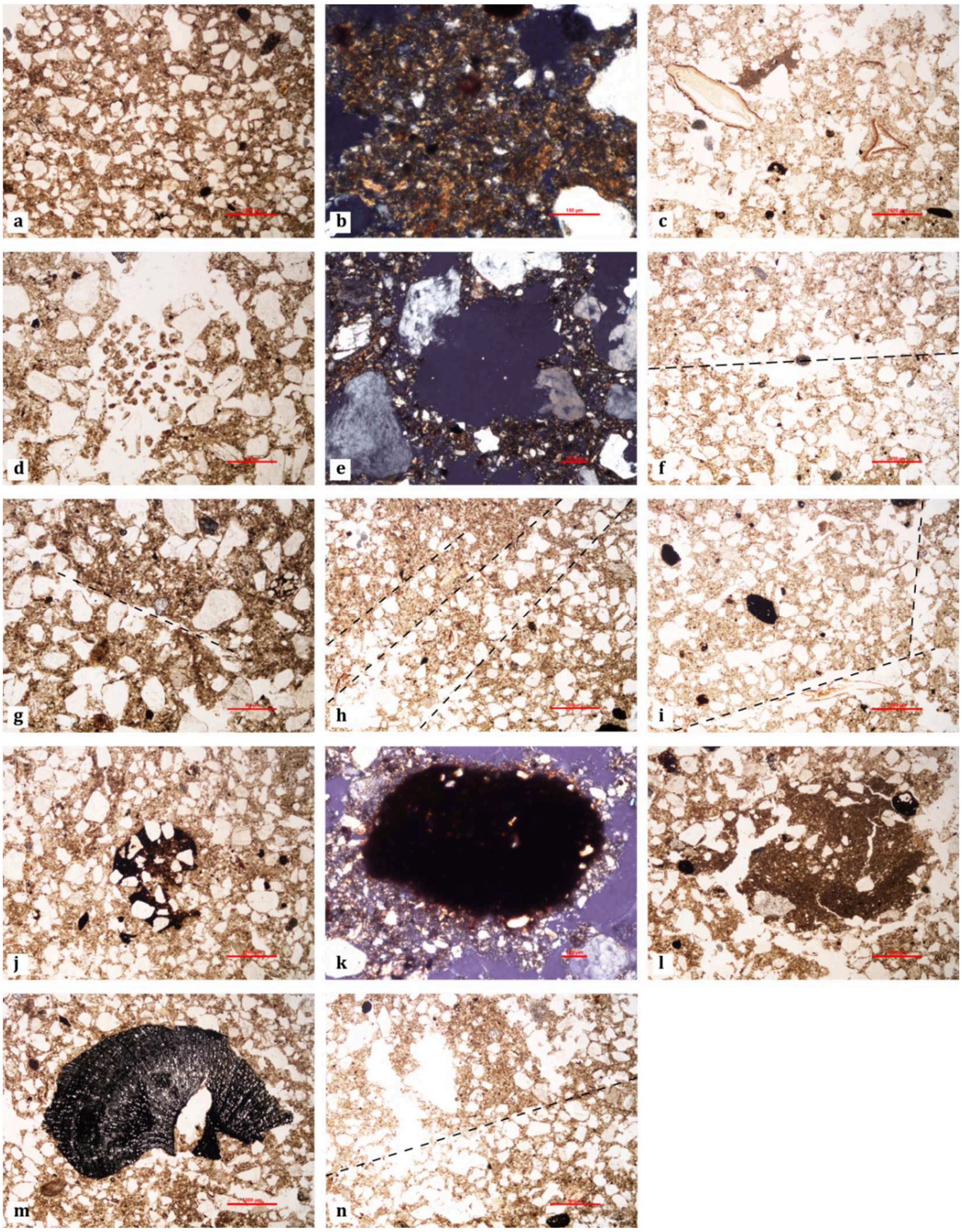


Figure 9. Details of thin sections. a: coarse texture (PPL, × 2) (CRA1); b: fine texture (XPL, × 20) (CRA1); c: vegetal debris (PPL, × 2) (CRA4t); d: porosity of type 1 containing Enchytraeids excretions (PPL, ×2) (CRA4t); e: porosity of type 2 (XPL, ×10) (CRA3t); f: horizontally elongated cavity (PPL, × 2) (CRA4t); g: flattened cavities alignment (PPL, ×4) (CRA2); h: tilted sand particles alignments (PPL, × 2) (CRA4t); i: subhorizontal associated to a subvertical sand particles alignment (PPL, × 2) (CRA3t); j: sharp shape ferruginous nodule (PPL, × 2) (CRA2); k: indistinct shape ferruginous nodule (XPL, × 20) (CRA3t); l: silty-clayey aggregate (PPL, × 2) (CRA3t); m: piece of charcoals (PPL, × 2) (CRA4t); n: detail of an obvious limit, between a low porosity layer below and a high porosity layer above. This limit is underscored by a subhorizontal sand particles and flattened voids alignment (PPL, × 2) (CRA3t).

2.3.3.5 Limits

In the material, two types of limits can be distinguished. The first type is characterized by obvious limits and materialized by the conjunction of three characters (Figure 9n): (1) abrupt change, from bottom to top, between a low porosity layer to a high porosity layer; (2) subhorizontal sand alignments along the limit; and (3) horizontally flattened voids along the limit.

The second limit type is a gradual transition, from bottom to top, between a more porous zone to a less porous zone (Figure 10). The analysis of a 24 cm vertical section, combining CRA3t, CRA3d, CRA4t and CRA4d thin sections reveals 4 subhorizontal sharp limits that separate 5 layers. Within each of these layers, a transition between a lower zone, more porous, and an upper zone, less porous is underlined (Figure 10).

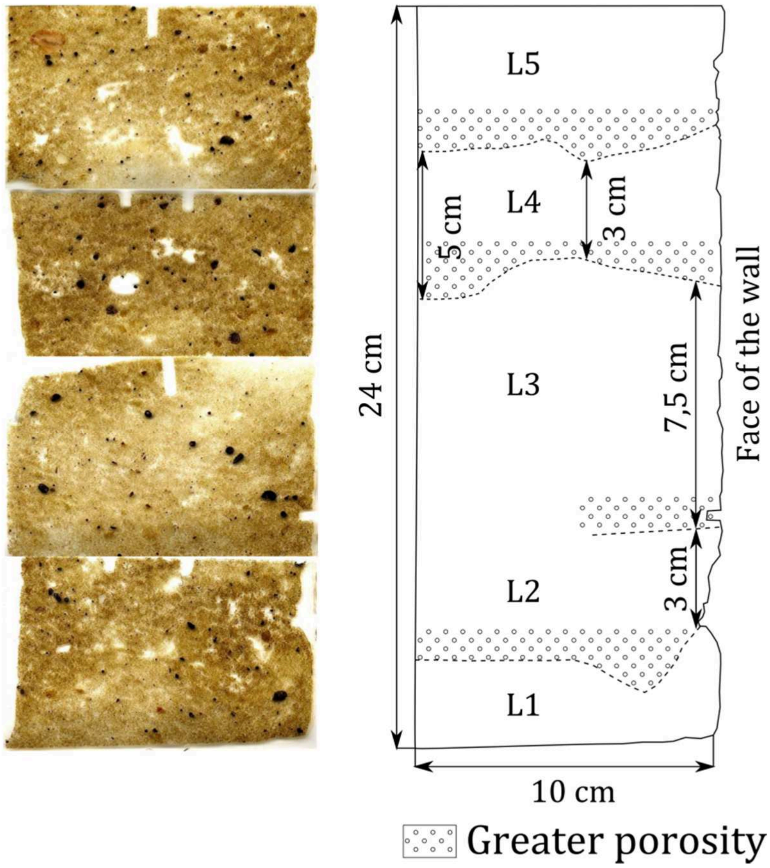


Figure 10. Vertical cross section, reconstructed thanks to 4 thin sections (CRA3t, CRA3d, CRA4t and CRA4d). Obvious limits are pictured by dotted lines. Obvious limits separate 5 layers, named L1 to L5, wherein porosity transition is underlined.

2.3.4 Discussion

2.3.4.1 Representativeness

Samplings concern a portion of 24 cm vertically and 20 cm horizontally in a 4.7 m high, 5 m long and 0.5 m thick wall. The representativeness of this sampling has to be discussed.

At the time of the construction, earth excavation was performed when required. Therefore, the rammed earth layers and lifts record the variations of the earth employed, more or less mitigated by the excavation, transportation and preparation stages. The contrast in earth composition is greater vertically, between the different rammed earth layers, than horizontally, along a single layer. Consequently, in a rammed earth wall, observations made on a vertical section could be considered as representative of all the entire layers intersected by this section. Contrariwise, these observations cannot be considered representative of layers located above and below this section.

2.3.4.2 Nature and source of the earth

Pedofeatures visible inside the wall are inherited from the history of the original soil in the ground and from modifications during construction stages. Once the earth compacted and dry, mechanisms driving soil particles transfer are stopped and the pedogenic dynamic is interrupted. The aim is to distinguish the features inherited from the original soil to that inherited from the modifications engendered by men during the construction process. This section focuses on features inherited from the original soil.

The presence of root debris (Figure 9c) or voids created after root decomposition (Figure 9d) demonstrated that the soil was excavated in a horizon relatively close to the surface, but the absence of leaf or branch debris reveals that the excavation does not concern the litter. The presence of ferruginous oxides (Figure 9j and 8k) denotes a pedogenesis in a waterlogged environment. Another feature helping to identify the original soil is the decarbonation of the micromass. Among the soil type of Bresse [136,137], the unique horizon that matches this description is the Eg horizon of type 1 (Figure 6). It is described as a 30-60 cm deep horizon, beige light with dark spots and concretions, more or less friable. The structure is polyhedral, fragile and root and worm porosity is high. This horizon, periodically waterlogged, is subjected to reduction, migration and precipitation of metallic oxides [136]. The noticeable difference between the wall material and the Eg horizon material concerns the structural arrangement of particles. This difference is hardly surprising, given the modifications and the compaction undergone by the earth in the rammed earth wall.

The absence of pedological data concerning the building site environment required soil recognition on the field via auger surveys. The objective of this recognition was the identification of the Eg horizon of type 1 soil, closest to the construction. As this kind of soils is only encountered in high topographic positions, the surroundings of the site, as well as the plateau of Balvay, were explored (Figure 5 and Figure 6). Among the horizons identified (Figure 7), horizon 2 of the profile *e* is the only one offering pedological characteristics compatible with the material used for the wall construction. In order to compare with the particle size distribution of the wall material, five samples were collected in a 60 cm vertical section of the profile *e*, at respective depths of 0/-12, -12/-24, -24/-36, -36/-48 and -48/-60 cm, and their particle size distribution and clay content were determined according to French standards NF P 94-056 (1996) and NF P 94-057 (1992) (Figure 11).

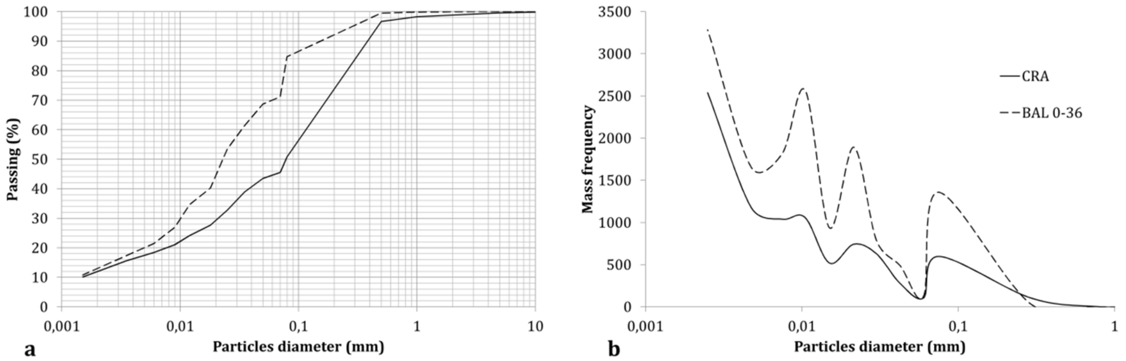


Figure 11. Comparison between particle size distributions and mass frequency of the rammed earth wall material (CRA) and material collected during the Balvay plateau survey, between 0 to 36 cm depth (BAL 0-36).

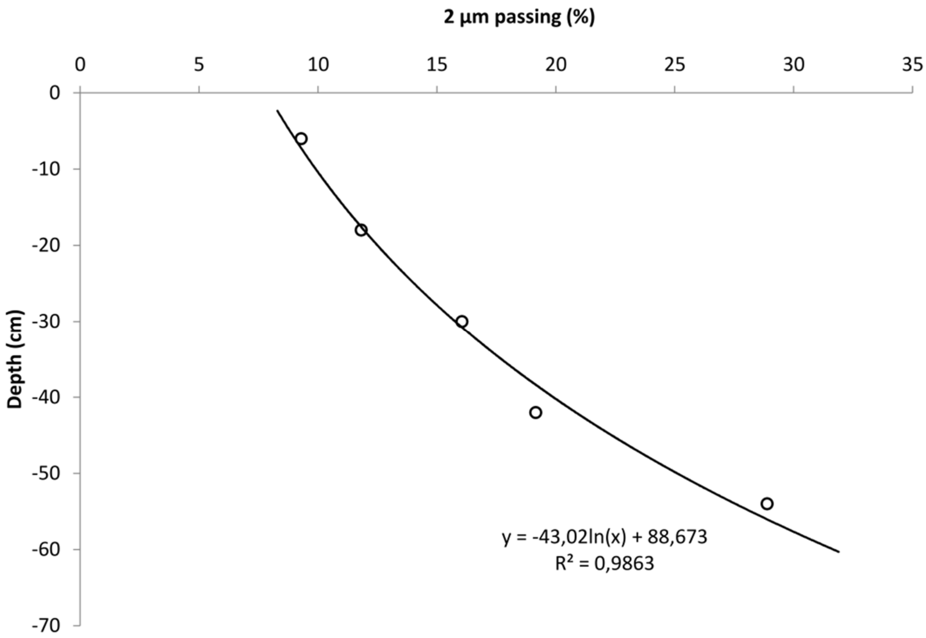


Figure 12. Clay content (2 µm passing) evolution with regard to depth of the e survey, located on the Balvay plateau.

In a first step, the average depth of excavation is determined according to the soil clay content. The clay content of the material of the wall is 11 %. On the profile *e* (Figure 7), 11 % clay content corresponds to a -17 cm depth (Figure 12). The excavation of the material source should then concern a 0 to -34 cm layer of the soil of the Balvay plateau. In a second step, in order to confirm this assertion, the particle size distribution of the rammed earth wall material (CRA) and these of the material collected between 0 to -36 cm depth on the Balvay plateau (BAL 0-36), are compared (Figure 11). CRA material has a greater sand fraction (30% by mass) than BAL 0-36 material. However, the points of inflection of the particle size distribution of the CRA material at 0.02, 0.05 and 0.07 mm are also observed on the particle size distribution of the BAL 0-36 material (Figure 11). The mass frequency representation confirms this observation (Figure 11). The difference can be attributed to the natural variability of the soil. The granulometric signatures of these two materials can be regarded as similar.

The material source of the rammed earth wall can be identified on the Balvay plateau, located 1 km east to the site (Figure 5). The construction is dated 1860. The network and mean of transportation of this time enable us to envisage the carriage of the earth over such a distance. The transportation of the 12 m^3 of earth required for wall construction corresponds to 6 tumbrel travels. The excavated horizon is just below the humiferous horizon and principally concerns the Eg horizon present between -5 to -35 cm depth. This is in line with what is commonly asserted in the literature on the origin of the materials for rammed earth construction, that refer to subsoil [82,83,145]. Considering a 30 cm thickness of soil excavated, the surface excavated to build the wall is estimated to 40 m^2. The same calculation performed for the entire building gives an excavated area of approximately 800 m^2. The selection of a particular horizon, located at least 1 km away, requiring excavation of soil on such a large surface area, tells us how carefully the choice and the excavation of the earth for construction was made by the 19th-century craftsmen.

2.4 Identification and quantification of earth resource at regional scale – application to cob in Brittany

2.4.1 Introduction

In section 2.4 a new methodology to identify and quantify earth material resources is proposed. This new methodology is based on the cross-referencing of spatialized pedological and heritage data. Pedological particularities of areas containing earth heritage are highlighted and these particularities are used to propose criteria to assess the suitability of soils for vernacular earth construction and scale of availability of the resource. This new methodology was employed for the first time in Brittany (France) and can be extended to regions having heritage and soil information. For this study, Soils of Brittany [146] and the Cultural Heritage of Brittany databases [147] were used.

In Brittany the vernacular earth construction technique is cob. The cob technique employs earth elements in a plastic state, implemented wet and stacked to build a monolithic and load-bearing or freestanding wall (section 1.4.1). This methodology deals with cob, but it can be expanded to other earth construction techniques, like rammed earth or adobe masonry.

2.4.2 Suitability of soils for cob

Some authors have characterized earth materials collected inside or next to old cob walls [18,91,93,121,123,148–152]. Results are too few and incomplete to summarize. However, vernacular cob earth textures were defined in the literature as loam [153–155], clay [16,76,80,117,127,156–162], silt [16,126,127,148] or clayey-silt [16,73,77,127] soils.

Silts, sands and gravels were identified as the granular skeleton that provides strength to the material [34,65,91,150,163]. Well-graded soils were preferred since their packing structure allowed good space filling properties that increased cob density, and therefore its mechanical strength [34,65,150]. Clay was identified as the binder that brings cohesion to the material [150]. If clay content was too low, cob material crumbled [150,163,164]. Nevertheless, clay content also governs the drying shrinkage of the cob mixture. If clay content was too high, large shrinkage cracks weakened the material [150,163,164]. As for earth plasters (section 4.3.3.3), there is an optimum clay content for cob, thought to be around 20 % [13,22,121]. Thus, suitability of soil for cob construction depended on clay content and particle size distribution. This is why some authors proposed earth-grading envelope to attest of their suitability for cob construction [13,22,36,37,61,120–122]. However, most of the grading curves of earth collected in old cob buildings did not fit inside those grading envelopes [91,93,115,123]. Consequently, these grading envelopes failed to give a full account of past cob masons knowledge.

2.4.3 Methodology description

2.4.3.1 Soil suitability determination

The relative densities of earth buildings are an indicator of the suitability of soils for earth construction [115]. Relative densities were calculated by cross-referencing between heritage and soil databases covering the same geographical area. The spatialized heritage database must provide homogeneous information on the vernacular architecture of the studied area and must concern all vernacular materials (timber, stone, earth, solid bricks). The described methodology is designed for the French soil cartographic representation called "*Référentiel Régional Pédologique*" (RRP), but can be adapted for other cartographic representations.

Soil cartographic representation by the RRP is set of polygons, spatially delineated, defining Soil Map Units (SMUs) [165]. Since soils show rapid variations in three dimensions, each SMU corresponds to a soil landscape, i.e. a collection of soils, defined as a Soil Type Unit (STU), developed in a common environment. Each SMU includes 1 to 10 STUs which are not spatially delineated [146,166] (Figure 13). Each STU is divided into strata, representing the spatial variability of soil. Pedological characteristics of SMUs, STUs and strata (such as deepness and thickness, texture and Cation Exchange Capacity) are gathered in a semantical database (Figure 13).

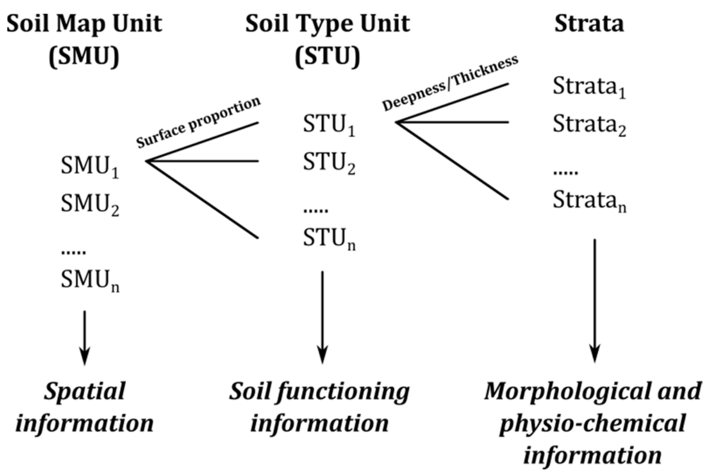


Figure 13. Pedological database: Soil Map Units (SMUs) are a spatialized depiction of soil landscapes at a scale of 1:125000, SMUs are composed of a proportion, expressed in surface, of various Soil Type Units (STUs) and STU consist of several strata. Only SMUs are delineated.

Heritage and pedological data are combined in a Geographic Information System so that the total heritage and earth heritage number of buildings, *TOT_SMU* and *EARTH_SMU*, respectively, can be determined for each SMU. The total and earth heritage building number of a SMU are attributed to the STUs that compose the SMU with respect of the surface proportion of STUs in the SMU ($SURF\_STU_{SMUi}$). The number of total heritage and earth heritage buildings of a STU, *TOT_STU* and *EARTH_STU*, respectively, are the sum of total or earth heritage buildings of the STU on the i^{th} SMUs inside which it is found (Figure 13):

$$TOT\_STU = \sum_i SURF\_STU_{SMU_i} \times TOT\_SMU_i \qquad (1)$$

$$EARTH\_STU = \sum_i SURF\_STU_{SMU_i} \times EARTH\_SMU_i \qquad (2)$$

In order to discuss the relative densities of vernacular earth buildings of the studied area, the frequency of earth buildings ($FREQ_{STU}$) are calculated for each STU:

$$FREQ_{STU} = \frac{EARTH\_STU}{TOT\_STU} \qquad (3)$$

Earth frequencies of STUs go from 0 to 1 and are divided into 11 frequency classes (Table 1). The frequency describes the suitability of STUs with regard to earth construction: the higher the frequency, the higher the suitability. The absence of earth heritage can reflect a poor suitability of available soils but this can also be explained by historical or social reasons. Consequently, suitability of soils is assessed using frequency classes greater than 1%, but it is not possible to state that characteristics of strata with frequencies lower than 1% are not compatible with earth construction. The frequency of a stratum ($FREQ_{STRATA}$) is assumed to be equal to the frequency of its STU ($FREQ_{STU}$).

Table 1. Frequency classes of earth buildings within STU. The frequency describes the suitability of the STU with regard to earth construction, the higher the frequency, the higher the suitability.

Frequency *(FREQ)*	Frequency classes *(CLASS)* (%)
0.9 - 1.0	90 - 100
0.8 - 0.9	80 - 90
0.7 - 0.8	70 - 80
0.6 - 0.7	60 - 70
0.5 - 0.6	50 - 60
0.4 - 0.5	40 - 50
0.3 - 0.4	30 - 40
0.2 - 0.3	20 - 30
0.1 - 0.2	10 - 20
0.01 - 0.1	1 - 10
0.0 - 0.01	0 - 1

The standard deviation σ_FREQ_{STU} of $FREQ_{STU}$ is calculated as below:

$$\sigma\_FREQ_{STU} = \sqrt{\frac{FREQ_{STU} \times (1 - FREQ_{STU})}{TOT\_STU}} \qquad (4)$$

A maximum standard deviation $\sigma\_FREQ_{STU\_MAX}$ is set by the researcher, in order to exclude outlier values.

In order to ensure that the data is representative, a minimum total heritage building per STU, n_{STU}, is calculated for a 95% confidence interval, a margin of error e and for total heritage buildings of the STU N:

$$n_{STU} = \frac{1.96^2 \times N}{1.96^2 + (2e)^2 \times (N-1)} \qquad (5)$$

Consequently, only STUs having a standard deviation σ_FREQ_{STU} lower than $\sigma\_FREQ_{STU\_MAX}$ and counting more than n_{STU} total heritage buildings are taken into consideration in the analysis.

Topsoil is rich in organic matter and was therefore inappropriate for construction purpose. Since soil excavation was traditionally made by hand, only soil near the surface was used, i.e. a large surface area and a thin layer of soil below the topsoil (section 3.3.2.1).

This is why organo-mineral (A, LA, H) and deep (appearance depth > 50 cm) strata were not considered in the analysis.

Pedological characteristics (*CHARACTER*) studied are clay, silt, sand, gravel content and Cation Exchange Capacity (CEC). They were determined during the soil of Brittany campaign and are available in the pedological database [146,166]. Particle size distribution of the pedological database was determined by wet sieving for fractions greater than 50 µm and by Robinson pipette method for smaller fractions, according to French Standard NF X 31-107 [167]. CEC of the database was determined using the Metson test method [168], according to French Standard NF X 31-130 [169].

The pedological database contains modal, and, when available, minimum and maximum value for each characteristic of strata. Minimum (*MIN*) and maximum (*MAX*) values illustrate the range of value that can vary spatially due to natural variations of soils, each strata resulting from various punctual observations. When minimum and maximum values were available, these variations were taken into account by calculation of an estimated confidence interval. As the average and standard deviation are unknown, a half-confidence interval ($CONF\_INT_{STRATA}$) was estimated as the third of the range of the values:

$$\mathrm{CONF\_INT_{STRATA}} = \frac{\mathrm{MAX - MIN}}{3} \quad (6)$$

Consequently, the confidence level of the estimated confidence interval is not determined.

For each frequency class i ($CLASS_i$), the average value of each characteristic ($CHARACTER_{STRATAj}\_CLASS_i$), weighted by the earth frequency of the j^th^ strata ($FREQ_{STRATAj}$) is calculated:

$$\overline{CHARACTER_{STRATA_i}\_CLASS_i} = \frac{\sum_{i,j} CHARACTER_{STRATA_j}\_CLASS_j \times FREQ_{STRATA_j}}{\sum_i FREQ_{STRATA_j}} \quad (7)$$

For each frequency class i ($CLASS_i$), the average value of confidence interval of each characteristic ($CONF\_INT_{STRATAj}\_CLASS_i$), weighted by the earth frequency of the j^th^ strata ($FREQ_{STRATAj}$) is calculated:

$$\overline{CONF\_INT_{STRATA_j}\_CLASS_i} = \frac{\sum_{i,j} CONF\_INT_{STRATA_j}\_CLASS_j \times FREQ_{STRATA_j}}{\sum_i FREQ_{STRATA_j}} \quad (8)$$

Finally, the minimum and the maximum value of a characteristic, for a frequency class, $MIN_{CHARACTER}\_CLASS_i$ and $MAX_{CHARACTER}\_CLASS_i$, respectively, are calculated:

$$MIN_{CHARACTER}\_CLASS_i = \overline{CHARACTER\_CLASS_i} - \overline{CONF\_INT\_CLASS_i} \quad (9)$$

$$MAX_{CHARACTER}\_CLASS_i = \overline{CHARACTER\_CLASS_i} + \overline{CONF\_INT\_CLASS_i} \quad (10)$$

2.4.3.2 Earth resource quantification

Clay, silt, sand, gravel content and CEC minimum and maximum values of each frequency class are used to identify strata suitable for earth construction in the pedological database.

The volume of earth suitable for construction for each frequency class (VOL_EARTH_{CLASSi}) is the sum of the volume of strata suitable for construction:

$$VOL\_EARTH_{CLASS_i} = \sum THICK_{STRATA} \times SURF\_STU_{SMU} \quad (11)$$

The volume of earth is calculated considering several frequency classes. The classes to be considered for this calculation are set by the researcher:

$$VOL\_EARTH = \sum_i VOL\_EARTH_{CLASS_i} \quad (12)$$

And the proportion of soils suitable for earth construction ($PROP\_SOIL$) in the studied area is:

$$PROP\_SOIL = \frac{VOL\_EARTH}{VOL\_SOIL} \quad (13)$$

Where VOL_SOIL is the volume of all soils of the studied area.

To provide a cartographic representation of the resource availability, the volume of soils suitable for construction (VOL_EARTH_{SMUi}) is calculated for each SMU:

$$VOL\_EARTH_{SMU_i} = \frac{\sum VOL\_EARTH\_STU_{SMU_i}}{n\_STU_{SMU_i}} \quad (14)$$

With $VOL\_EARTH\_STU_{SMUi}$ calculated according to equation (11) and n_STU_{SMUi} the number of STU in the considered SMU. Resource availability is also displayed by surface. The surface of a SMU suitable for earth construction ($SURF\_EARTH_{SMUi}$) is the sum of the surface of the STUs of this SMU suitable for earth construction ($SURF\_EARTH\_STU_{SMUi}$):

$$SURF\_EARTH_{SMU_i} = \sum SURF\_EARTH\_STU_{SMU_i} \quad (15)$$

2.4.4 Application to Brittany (France)

2.4.4.1 Study area

Brittany is part of the Armorican Massif. This Massif is the result of, at least, three orogenies. Rocks of this geological domain are mostly old sedimentary rocks, more or less metamorphosed (sandstone, schist), metamorphic rocks (gneiss), magmatic rocks (granite, rhyolite) and loess deposits [170–172]. Paedogenesis of the massif is dominated by darkening and leaching. Locally, podsolization and a paleopedogenesis, marked by a fersiallitization, are mentioned [173].

Among Armorican rocks, Brioverian schists are sensitive to alteration and thus produced thick soils that favoured cob construction [77,93,116,174,175]. Regoliths deriving from other local parental materials (granite, sandstones, Cambrian schists) were also employed for cob construction [93]. Nevertheless, the correlation between geology and cob heritage distribution in Brittany did not provide satisfactory results [175].

2.4.4.2 Heritage and pedological databases

Since 1964, historians and architects of the *Service du Patrimoine Culturel* of Brittany have carried out a systematic field inventory of regional cultural heritage and maintained a database [147]. This heritage database was homogenized in order to create a unique point database, counting 113 824 entities (buildings, castle mound, archaeological sites, crosses, statues, etc.). To focus on vernacular building heritage, the items without information on building materials, built after 1925, of military or religious character, or built with a modern material (steel, glass, concrete, hollow brick) were removed from the database. Subsequently, a clean database of 48 230 heritage buildings was obtained. Among these 48 230 buildings, 7 133 were identified as cob buildings, which represents 14.8% of the studied heritage (Figure 14) and 24% of the estimated total cob heritage of Brittany [77]. These buildings date back as far as the 16th century (Figure 15). Other heritage building materials were stone, timber and solid brick.

The heritage survey of Brittany is not yet complete. Municipalities having no data were therefore not considered in this study. The study area represents 54% of the total surface of Brittany and the proportion of study area inside and outside the vernacular cob area, determined using literature data [174–177], is well balanced (Figure 14). The geographical distribution of the study area reflects the heritage distribution of Brittany and is therefore considered as satisfactory.

Soil information at 1:250,000 map scale in Brittany was obtained in the framework of the "*Référentiel Régional Pédologique"* (RRP) project, started in 2005, certified in 2012 and available online [146].

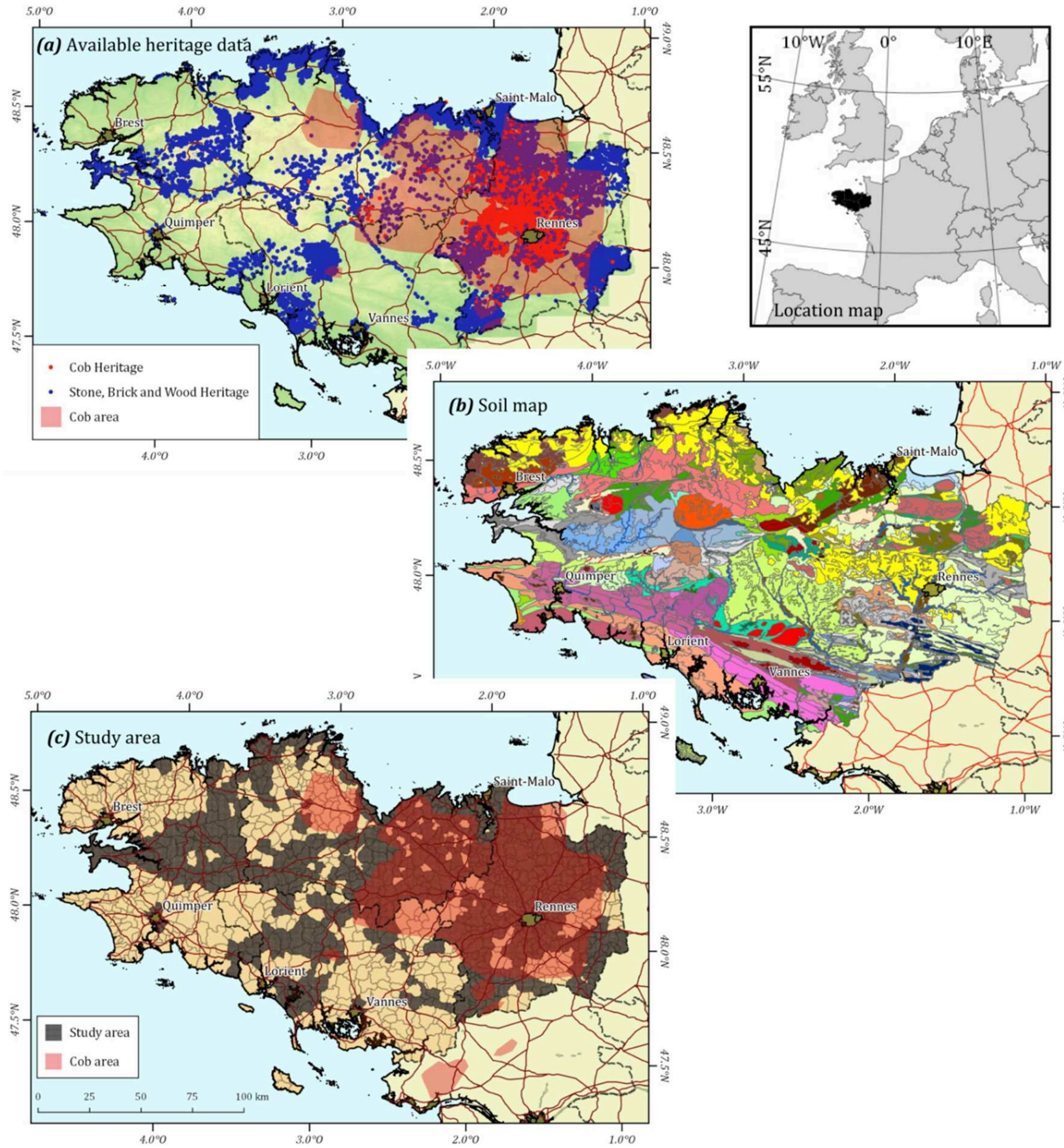


Figure 14. Maps of available information in Brittany concerning (a) Heritage database [147]*, and vernacular cob area of Brittany* [174–177]*; (b) 1:250,000 soil map figuring complex Soil Map Units (SMU)* [146]*; (c) map of municipalities possessing heritage data, defining the study area, together with vernacular cob area of Brittany* [174–177]*.*

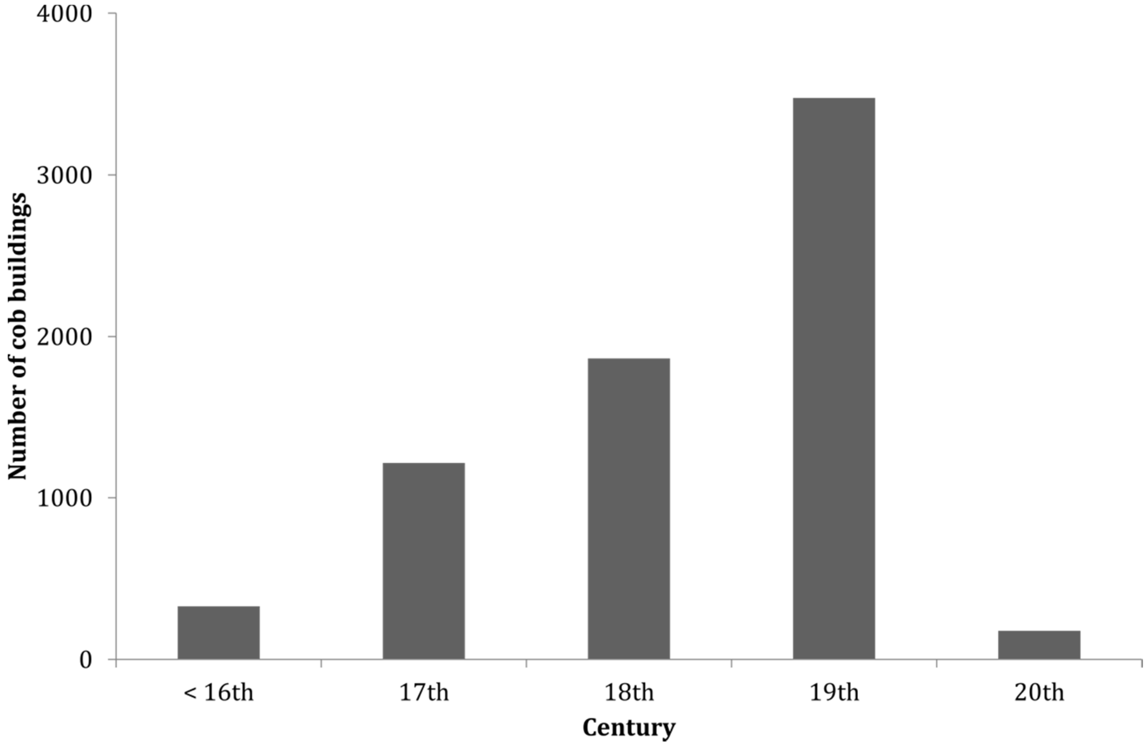


Figure 15. Temporal distribution of cob buildings of the studied area. Few cob buildings are attested for the 20th century since cob construction fell into disuse at the beginning of the 20th century.

2.4.4.3 Data processing

The minimum total heritage building per STU, n_{STU}, is calculated according to equation (5), considering N = 48230 and e = 0.1: n_{STU} = 96. The $\sigma\_FREQ_{STU\_MAX}$ is set to 0.03. Among 288 STUs, 68 STUs verify these two parameters and are considered for the analysis. Five of these STUs had missing information and were therefore not considered for the analysis. Cob frequency ($FREQ_{STU}$), frequency class ($CLASS$) and standard deviation (σ_FREQ_{STU}) of the 63 STUs employed for the analysis are shown in Table 1. Frequencies range from 0.00 to 0.49. As a consequence, 6 frequency classes were considered (Table 2).

Table 2. Frequency, frequency class and standard deviation (σ_FREQ$_{STU}$) of Soil Type Unit (STU), calculated according to section2.4.3.1. Description of STUs can be found online: http://www.sols-de-bretagne.fr/ [146].

STU	*Cob frequency (FREQ$_{STU}$)*	*Frequency class (CLASS) (%)*	*Standard deviation (σ_FREQ$_{STU}$)*
247	0.49	40-50	0.018
289	0.42	40-50	0.022
183	0.37	30-40	0.016
346	0.35	30-40	0.029
286	0.32	30-40	0.018
248	0.31	30-40	0.011
85	0.31	30-40	0.018
61	0.27	20-30	0.015
51	0.26	20-30	0.009
336	0.26	20-30	0.020
246	0.25	20-30	0.019
251	0.25	20-30	0.016
92	0.24	20-30	0.027
86	0.23	20-30	0.012
442	0.23	20-30	0.017
184	0.21	20-30	0.021
257	0.17	10-20	0.014
431	0.17	10-20	0.006
188	0.16	10-20	0.026
66	0.16	10-20	0.024
512	0.15	10-20	0.022
63	0.15	10-20	0.024
282	0.14	10-20	0.021
112	0.13	10-20	0.022
182	0.12	10-20	0.026
255	0.11	10-20	0.018
340	0.10	1-10	0.014
56	0.09	1-10	0.015
21	0.07	1-10	0.017
441	0.07	1-10	0.012
254	0.06	1-10	0.025
65	0.06	1-10	0.013
62	0.06	1-10	0.024
13	0.06	1-10	0.013
243	0.05	1-10	0.018
281	0.05	1-10	0.011
82	0.04	1-10	0.005
180	0.04	1-10	0.008
331	0.04	1-10	0.017
53	0.03	1-10	0.015
26	0.03	1-10	0.012
245	0.03	1-10	0.010
54	0.02	1-10	0.003
14	0.01	0-1	0.004
57	0.01	0-1	0.005
68	0.01	0-1	0.005
113	0.01	0-1	0.004
59	0.00	0-1	0.003
89	0.00	0-1	0.003
64	0.00	0-1	0.003
80	0.00	0-1	0.003
181	0.00	0-1	0.004
111	0.00	0-1	0.003
150	0.00	0-1	0.003
100	0.00	0-1	0.002
97	0.00	0-1	0.003
67	0.00	0-1	0.002
72	0.00	0-1	0.001
262	0.00	0-1	0.001
102	0.00	0-1	0.001
101	0.00	0-1	0.000
250	0.00	0-1	0.000
290	0.00	0-1	0.000

2.4.5 Results and discussion

2.4.5.1 Resource identification

Texture

Textures (clay, silt, sand and gravel contents) of pedological strata for 5 frequency classes are presented in Table 3, and the 20-50% cob frequency textures are shown in Figure 16. They do not exhibit any minimum gravel content, only a maximum value, ranging from 2% for 40-50% frequency class to 30% for the 1-10% frequency class (Table 3), indicating that vernacular cob earth in Brittany did not necessary contained gravels and that a low gravel content was observed.

Gravels are sometimes observed in vernacular cob walls and their role is thought to temper the drying shrinkage effect. However, most of the time, natural fibres were added in order to play this role (section 3.3.4.2). Large gravels were usually removed from earth since they make the trampling of cob mixture difficult and disturb the wall faces rectification process (section 3.3.3.3). Consequently, past builders developed specific cob techniques adapted to earths with high gravel content, but, when possible, little or zero gravel content earth were preferred. Results are consistent with the constraints of the vernacular cob process.

Clay, silt and sand content of strata having an affinity with cob have a minimum and a maximum value (Figure 16, Table 3). These three granular fractions were therefore required for cob construction. The balance between these three fractions is clearly in favour of silts, since they represent 37% to 57% of the material (Figure 16, Table 3). Among the large variety of soils available in Brittany, cob heritage preferentially set up on silty soils (Figure 16).

Fine earth fraction (< 2 mm) represents the clay, silt and sand content of earth without coarse elements (Clay + Silt + Sand = 100%). The textures of fine earths are depicted by points in the GEPPA texture triangle [114], conventionally used for French soil identification (Figure 17).

Table 3. Texture, Cation Exchange Capacity (CEC) of soils and Cation Exchange Capacity of clay fraction (CL_CEC), according to cob frequency classes. Values are given in percentage by mass.

Frequency class (%)	Clay (0 - 2µm) (%)		Silt (2 - 50µm) (%)		Sand (50µm - 2mm) (%)		Gravel (>2mm) (%)		CEC ($cmol^{+}.kg^{-1}$)		CL_CEC ($cmol^{+}.kg^{-1}$)
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Average
40-50	9	17	57	74	13	28	0	2	2.8	5.5	31
30-40	11	22	54	70	10	25	0	9	2.8	5.3	26
20-30	12	22	46	63	13	31	0	20	3.0	5.5	24
10-20	12	22	37	58	17	37	0	21	3.6	6.2	28
1-10	10	21	32	55	16	36	2	30	3.0	5.4	25

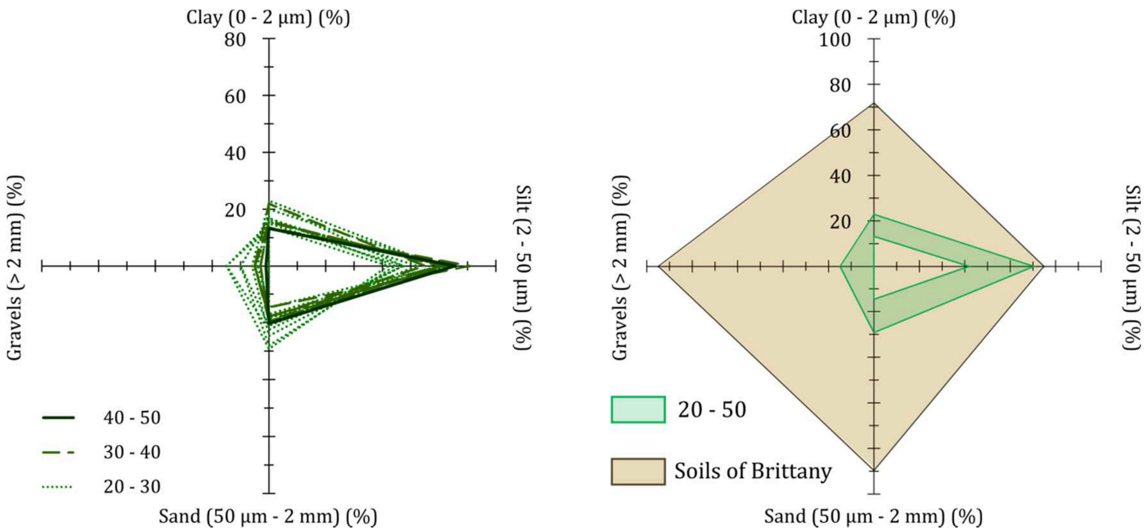


Figure 16. Texture of soils of 40-50 %; 30-40 % and 20-30 % cob frequency classes (left) and comparison of these textures (20-50 % cob frequency) with all soils of Brittany (right). The coloured surfaces of the radar graphical representation allow an easy comparison between recommended textures, but only the extremum clay, silt, sand and gravel contents are to be considered.

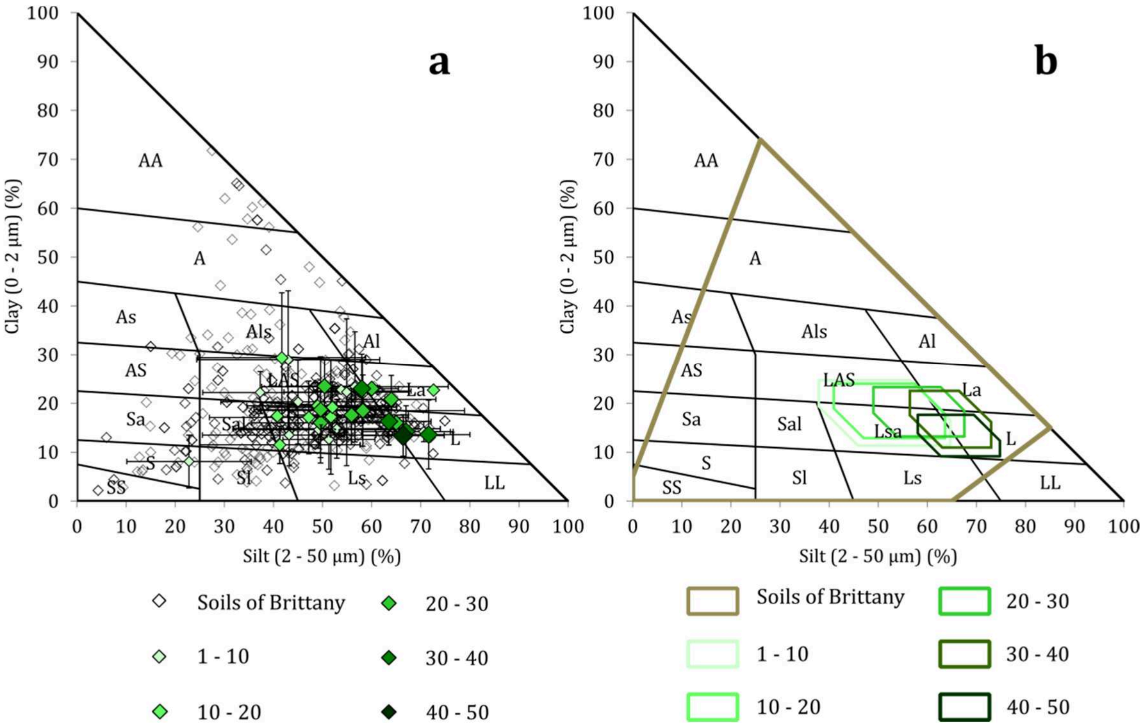


Figure 17. Texture of fine earth of strata of Brittany according to their cob frequency in percentage. Strata values are presented on a (diamond are mode values and error bars are estimated confidence interval) and frequency classes values, calculated according to section 2.4.3.1 are shown on b. Data are projected in the texture triangle of reference for French soils, defined by the GEPPA (A = clay; L = silt; S = sand). In this representation, regardless of the gravel content, sum of clay, silt and sand content is 100%.

Among soils of Brittany, textures of fine earths with a 1-50% cob frequency are the siltiest (Figure 17). The texture of fine earth of 40-50% cob frequency is mostly silty, and with lower cob frequencies, the silt fraction decreases in favour of the sand fraction and maximum clay content slightly increases (Figure 17, Table 4).

Table 4. Texture of fine earth (clay + silt + sand = 100%), of soils according to cob frequency classes. Values are given in percentage by mass.

Frequency class (%)	*Clay (0 - 2µm) (%)*		*Silt (2 - 50µm) (%)*		*Sand (50µm - 2mm) (%)*	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
40-50	9	18	58	75	13	28
30-40	11	23	56	73	11	26
20-30	13	23	49	68	14	33
10-20	13	24	41	64	19	40
1-10	11	25	38	65	19	43

Comparison of texture results with existing recommendations

Different grading envelopes are proposed in the literature [13,22,121,122]. These recommendations were adapted and are presented in Figure 18 and Figure 19a.

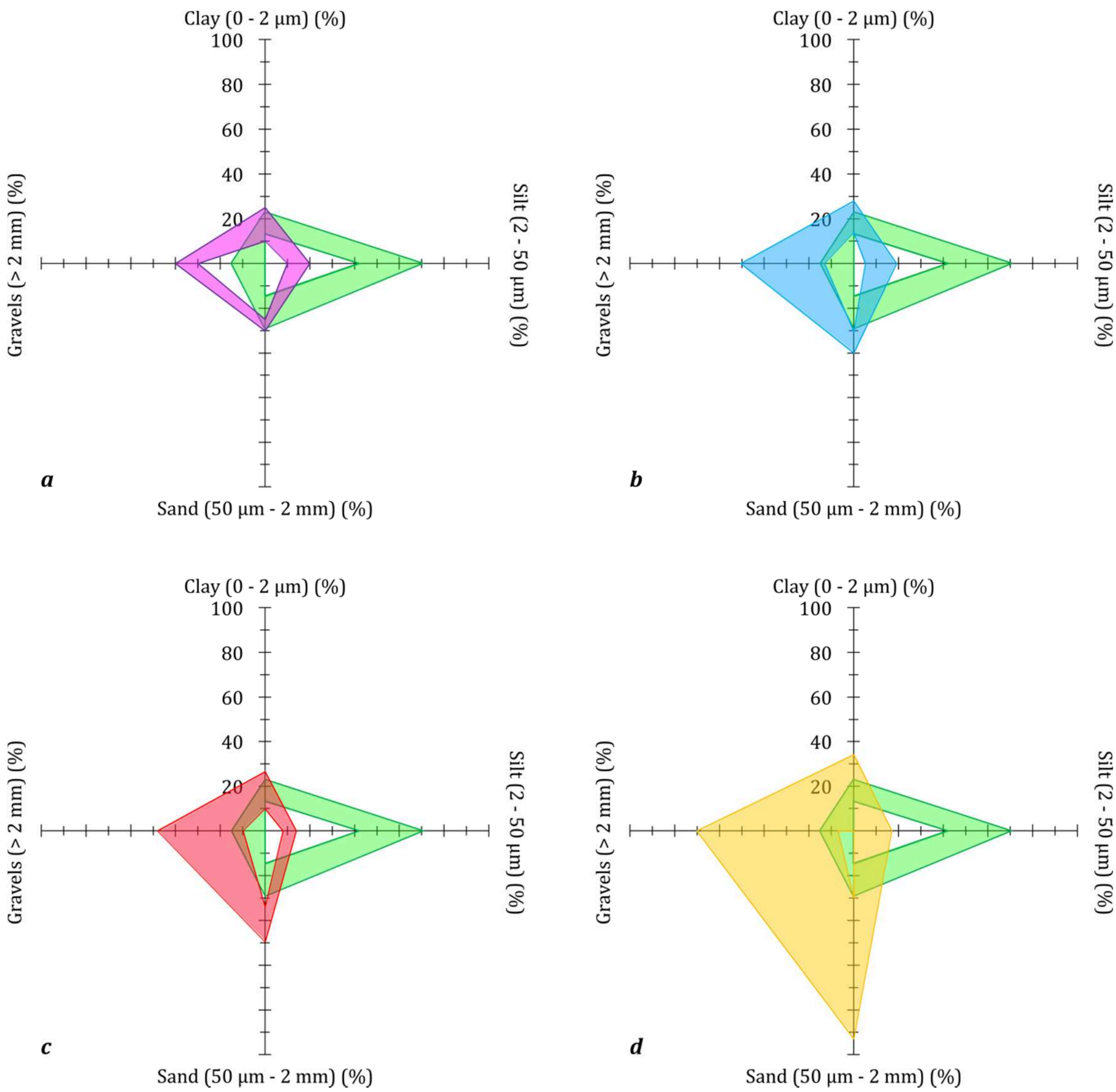


Figure 18. Comparison between texture of soils with a 20-50 % cob frequency identified in Brittany and recommended texture available in the literature, proposed by Morris [13] *(a), Harries et al.* [121] *(b), Keefe* [22] *(c) and Jaquin and Augarde* [122] *(d). The coloured surfaces of the radar graphical representation allow an easy comparison between recommended textures, but only the extremum clay, silt, sand and gravel contents are to be considered.*

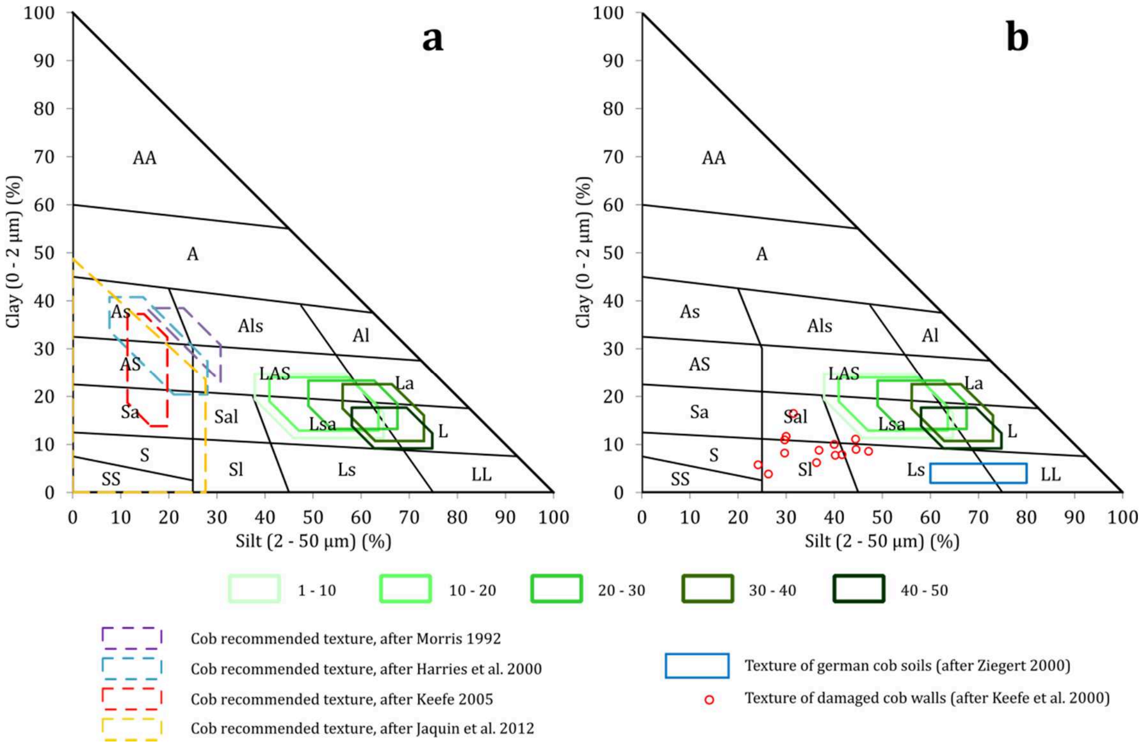


Figure 19. Confrontation of texture of fine earth identified as suitable for vernacular cob construction in Brittany with, a: cob recommended texture available in the literature [13,22,121,122]*, and b: texture of fine earth of German cob soils* [155] *and damaged cob walls built with soils derived from Permo-Triasic rocks* [123]*. Data are projected in the texture triangle of reference for French soils, defined by the GEPPA (A = clay; L = silt; S = sand). In this representation, regardless of the gravel content, sum of clay, silt and sand content is 100%.*

The comparison between texture of strata, identified as having an affinity with cob heritage in Brittany, with recommended textures for cob available in the literature (Figure 18) indicates that: (1) clay content of cob with a 20-50% cob frequency is inside the literature recommendation; (2) recommendations from the literature propose a minimum gravel content, supporting the hypothesis that gravels are necessary for cob material, which contradicts the results of this study; (3) the balance between sand and silt is in favour of sand in the literature and in favour of silt in this study.

As for the texture of earth with coarse elements, the texture of fine earth within the cob area of Brittany widely differs from recommended texture of fine earths available in the literature (Figure 19a). The same difference has been highlighted by several authors for vernacular cob materials [91,93,115,123], vernacular adobe [87] and vernacular rammed earth materials (section 2.3.4.2). In fact, earth suitability recommendations are based on a theoretical laboratory approach, whereas vernacular soil selection is the result of time-tested empirical experimentations. Textures identified in this study enlarge the possible sources of earth suitable for cob construction and call into question recommendations available in the literature.

Comparison of texture results with existing data

Data on textures of cob heritage buildings are available for Germany [155] and the United Kingdom [123]. These data have been adapted and are presented in Figure 19b. Fine earth material of cob heritage in Germany, more precisely in Saxony, Saxony-Anhalt and Thuringia [155], have a sand/silt balance quite similar to high-frequency fine earth texture determined for cob in Brittany, but their clay content (2-6%) is smaller (Figure 19b).

In Devon (United Kingdom), it was demonstrated that traditional cob walls built with soils derived from Permo-Triasic rocks had a higher propensity to structural failure than those derived from the "Culm measure" rocks [123]. Textures of fine earths, from what the authors called a "high risk zone", labelled by red circles on Figure 19b, are outside the texture of fine earth identified for cob in this study. Results are therefore in accordance with those of Keefe et al. [123]. Nonetheless, even if considered as "high risk" materials, historical builders in Devon managed to carry out cob buildings with these earths. Thus, textures of earths identified as suitable for traditional cob in Brittany do not cover the entire textures of earths employed in Devon's vernacular cob. Since no information was provided on the texture of earth of undamaged cob walls, it was not possible to state if earths suitable for cob in Devon are inside or outside the cob area defined in the present study (Figure 19b).

Hence, the results of this study are relevant only for Brittany. Nevertheless, silty textures of fine earths seem to have been preferred by past builders, at least in Brittany and Germany.

Cation Exchange Capacity and clay

Cation Exchange Capacity (CEC) of a soil is intimately linked to the specific surface area of clay and organic matter content [178–181]. CEC of strata with a 10-50% cob frequency range from 2.8 to 6.2 $cmol^{+}.kg^{-1}$ (Table 3), whereas CEC of all strata of Brittany ranges from 0.5 to 106.0 $cmol^{+}.kg^{-1}$. Strata with a 10-50% cob frequency (Figure 20a) of Brittany exhibit CEC which corresponds to no or little organic matter content and low activity clay soils [182].

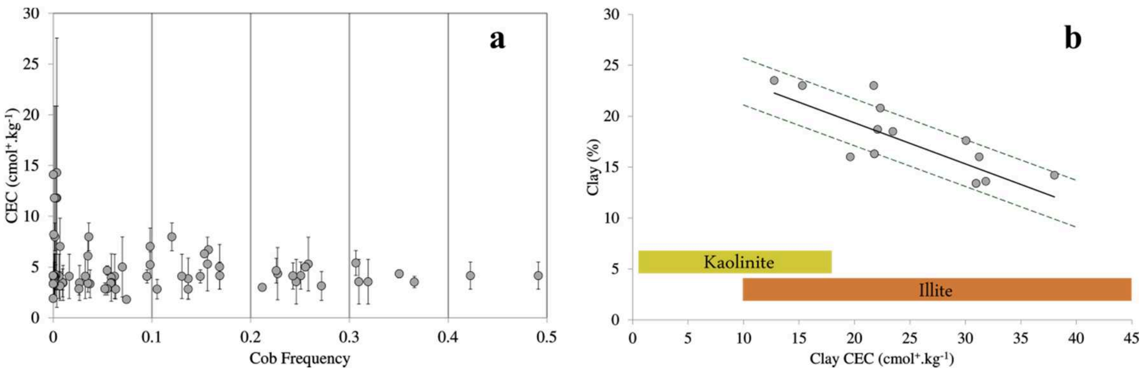


Figure 20. a: Cation Exchange Capacity (CEC) of strata of Brittany plotted against cob frequency, b: clay content of strata with a 20-50 % cob frequency plotted against the CEC of clay fraction (on right). A linear relationship is proposed between Clay content (CLAY) and Cation Exchange Capacity of Clay (CL_CEC) for cob in Brittany with a correlation coefficient of 0.78 and a standard error of 2.3. The solid line depicts this relationship and dotted lines depict the standard error.

The organo-mineral strata were not taken into account for the data analysis (section 2.4.3.1), thus organic matter content of strata considered in the analysis is very low, and its contribution to CEC is limited. Assuming that CEC can be attributed to clay only, the CEC of the clay fraction was calculated (CL_CEC, Table 3). According to their CEC, the clay fraction of strata with a cob affinity is mainly composed of Illite and Kaolinite clay types, i.e. clay with low or medium sensitivity to water (Table 3). This is in agreement with the literature: cob mixture is implemented at plastic state and drying shrinkage could generate wide cracks that might affect mechanical resistance.

In earths with a 20-50% cob frequency, when CEC of clay (CL_CEC) increases, the clay content decreases (Figure 20b): the more the specific surface of the clay, the less the required clay content. A linear relationship is proposed between Clay content (CLAY) and Cation Exchange Capacity of Clay (CL_CEC) for cob in Brittany with a correlation coefficient of 0.78 and a standard error of 2.3. This relationship, together with its standard deviation is presented in Figure 20b. The upper standard error line is the value above which the specific surface developed by clays might generate harmful shrinkage, and the lower standard error line is the value below which the specific surface developed by clays might not be enough to provide sufficient cohesion to the material. There is an optimum clay content (section 4.3.3.3) [183,184] and this optimum clay content decreases when CEC of clays increases (Figure 20b). This relationship was suspected for a long time and is highlighted in this study for the first time.

Pasts masons added elements to the cob mixture to play the role of shrinkage crack barriers, such as fibres, in order to employ earth that would have shrunk too much (section 3.3.4.2). As the fibre content and the cob variation technique employed for cob heritage buildings studied here are unknown, this might have affected the correlation coefficient of the clay content and clay CEC relationship (Figure 20b).

Earth and cob process

There are many variations of the vernacular cob construction process resulting from the adaptation of the technique to local environments (section 3.3.3.1). The earth could have been adapted to the cob process, for example by fibre addition (section 3.3.2.3), or the process could have been adapted to the earth, for example, the wall rectification technique (section 3.3.3.3). Thus, a strong link occurs between the available earth and the process employed. The frequencies calculated in this study are valid for vernacular techniques traditionally employed in Brittany, under this local climate and social context. The most widespread vernacular cob technique of Brittany consisted in treading earth and straw into a plastic consistency, stacking clods of cob into the wall, compacted by treading action and rectifying the faces of the walls by a trimming action (case (a), section 3.3.3.1). However, other cob techniques are encountered in Brittany. As no information is available about the technique employed for cob building construction in the heritage database, it is not possible to discuss the suitability of earth with any specific cob variation technique.

In the area of a given SMU, a high proportion of cob heritage indicates *a priori* (1) a large availability of earth, (2) a good quality of earth allowing easy implementation, (3) a high longevity of cob buildings and (4) a favourable cultural context. The frequency of earth buildings depends on the combination of these four factors. It is assumed that the highest frequency class depicts the most suitable soils of Brittany for vernacular cob construction.

Because these results need to be compared to those of other vernacular cob regions, they should be used only as a decision support tool for modern cob applications and not for standardisation purposes.

2.4.5.2 Resource quantification

The cob resource quantification was carried out according to section 2.4.3.2, considering a 10-50% cob frequency class. This large frequency class is thought to better reflect the earth availability in a modern context.

A geographical representation, by percentage of surface and by percentage of volume, calculated for each SMU, of soils suitable for cob in Brittany, is presented in Figure 21. Geographical distribution of cob heritage, drawn according to several literature sources [174–177] is also shown in Figure 21. Thanks to the percentage of available earth calculated, a quantitative estimation of the availability of the resource at regional scale is proposed in Table 5.

The availability of cob soils, expressed in surface, is greater to the northeast part of Brittany and well correlated with the geographical distribution of cob heritage, whereas there is no correlation between the geographical distribution of cob soils by volume and cob heritage (Figure 21). This result suggests that the geographical continuity of the resource is more important than the volume of the resource in order to allow the development of a local earth construction culture. Modern excavation provides access to resources that were not accessible by manual excavation means. The representation of the resource by surface should be regarded as a representation of the availability of cob soil in a historical context, and the representation by volume should be regarded as a representation of the availability of cob soil in a modern context.

Macroscale orders of magnitude of the volume of available soil resource for cob were calculated (Table 5). The volume of soil available for vernacular cob technique in Brittany was estimated at 6.8 billion m^3, i.e. 8.8 billion tonnes, and represents 23% of total soils of Brittany. The estimated proportion of the resource already consumed by past builders is 0.03%. The hypothetical consumption of the entire resource would enable the construction of 88 million homes and if all housing of Brittany were made of cob, 2.1% of the resource would have been consumed (Table 5). These figures illustrate the huge availability of earth material. These calculations are based on 10-50% cob frequency soils and considering vernacular cob technique only. Considering that it is possible to use other types of earths with mechanized cob, that skilled craftsmen are able to use earth outside the 10-50% cob frequency area and that other earth construction techniques could be employed, these orders of magnitude should, therefore, be regarded as minimum values in a modern earth construction context.

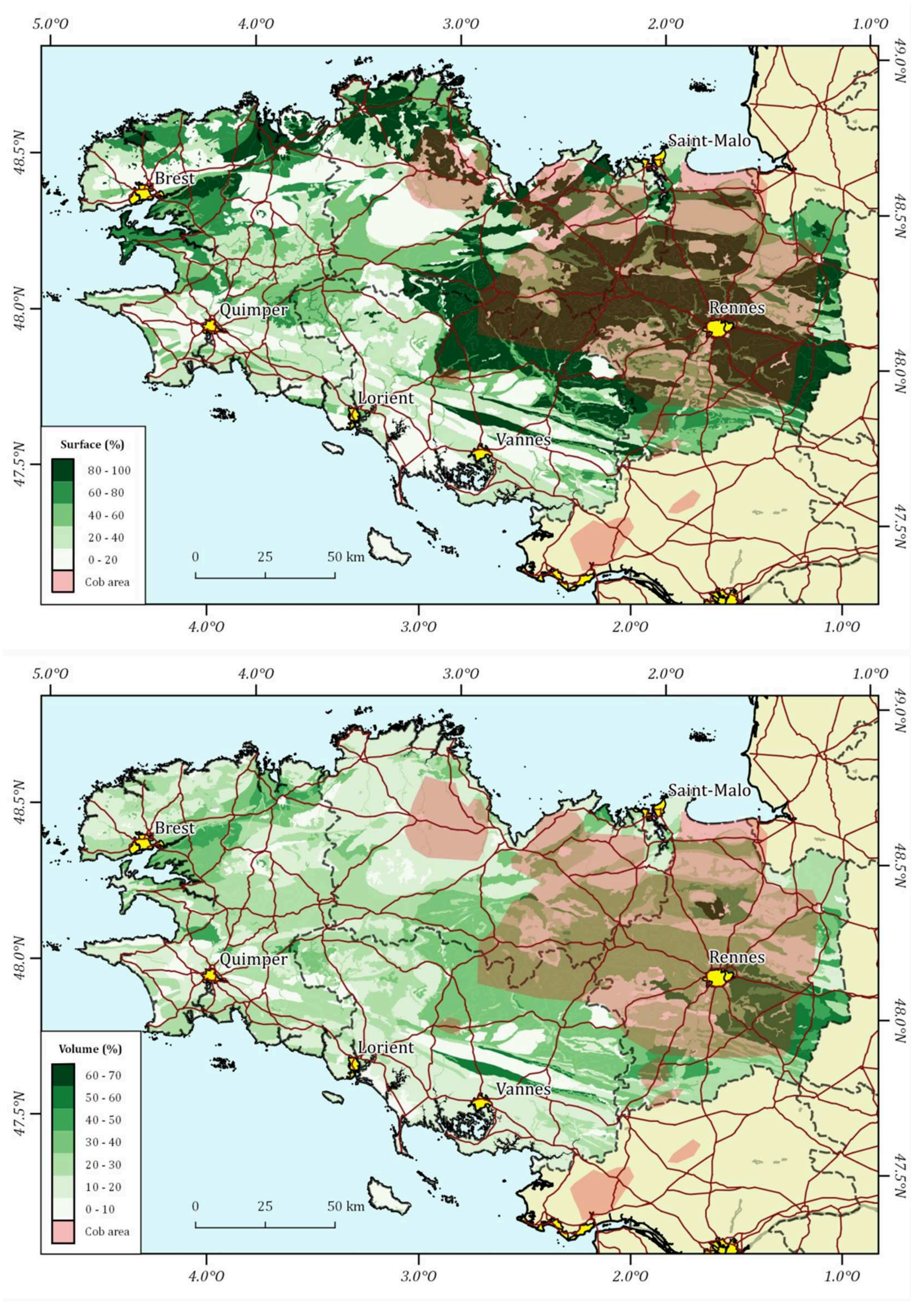


Figure 21. Map of soil resource availability for vernacular cob in Brittany, considering strata with a 10-50 % cob frequency; (a) by surface: sum of surface of STUs having at least one strata suitable for cob; (b) by volume: proportion by volume of strata suitable for cob, calculated for each SMU, and comparison with vernacular cob area [174–177].

Table 5. Estimation of soil availability for cob construction in Brittany, by volume, mass and proportion, estimation of the consummation of the resource by heritage and orders of magnitude of potential cob resource provided by earthworks.

Volume of soil identified as suitable for cob in Brittany (m^3)	6.8E+09
Mass of soil identified as suitable for cob in Brittany (t) *(1)*	8.8E+09
Proportion of soils of Brittany identified as suitable for cob (%)	23
Estimation of cob earth resource already consumed by cob heritage (%) *(2)*	0.03
Number of housing feasible, consuming the entire cob resource *(3)*	8.8E+07
Number of total housing in Brittany in 2013 *(4)*	1.8E+06
Resource consummation if all housing of Brittany were made of cob (%)	2.1
Landfilled soils suitable for cob in Brittany in 2012 (t) *(5)*	6.49E+05
Number of housing feasible, consuming suitable landfilled soils *(3)*	6490
Number of housing carry out in Brittany in 2013 *(4)*	12544
Cob potential market share in Brittany (%)	52

(1) considering a soil density of 1.3 $t.m^{-3}$
(2) considering 30 000 buildings and 100 t per building
(3) considering 100 t per building
(4) source: INSEE
(5) considering 23 % of excavated soils, source: Cellule Économique de Bretagne

Nonetheless, soil is a non-renewable material on the human time scale and it provides various ecosystem services concerning provisioning, regulating, cultural and supporting services [185]. Excavation of earth for construction might impact multifunctional roles of soil. Management of the consumption of this resource should, therefore, be carefully considered.

Currently, earthworks excavations generate large amounts of landfilled soils. In Brittany, 2.8 million tonnes of soils are landfilled every year. Considering that 23% of these landfilled soils are suitable for cob, in 2012, 0.6 million tonnes of earth were available in Brittany and would have enabled the construction of 52% of the individual housing of Brittany that year (Table 5). The resource of earths suitable for cob in Brittany is huge and earthwork excavations already provide large amounts of these earths every year. This high-quality construction material could be valued in the building sector, instead of ending up as waste in landfills.

2.5 Synthesis of chapter 2

Micromorphological analysis of samples collected in earth buildings, combined with pedological analysis, allows identifying precise location and depth of earth excavation. This methodology provides an accurate tool for earth source identification, but is time-consuming and thus cannot be employed to assess soil suitability at regional scale. The novel methodology, based on the cross-referencing of pedological and heritage data, proposed in this manuscript, permit the identification of the pedological characteristics and suitable classes of soils employed by historical masons, to draw a map of availability of earth material at regional scale, to quantify the resource availability, the recycling potential and the earth construction sector potential market share at regional scale. These two methodologies provide complementary tools allowing the study of soil suitability for earth construction.

The careful earth source selection made by historical builders for the construction of the Cras-sur-Reyssouze rammed earth farm highlights their sophisticated know-how. This result confirms the relevance of the vernacular earth construction rediscovering process. Texture results of cross-referencing soil and heritage data call into question recommendations available in the literature. Suitable soils for construction are often described as “clayey soils” and recommended textures proposed in the literature are most of the time sandy-clayey soils. However, results suggest that past builders might have preferred silty soils. Further investigations are needed to highlight the reasons for these differences. To go deeper in the discussion on the identification and quantification of soils for construction, the same methodologies should be applied to other regions with different earth construction techniques and climates.

Chapter 3 Description of vernacular earth construction processes

3.1 Introduction

The information that survived until nowadays derived from precious testimonies of past builders who have employed vernacular earth construction techniques. Nevertheless, testimonies are a narrow sample of the entire traditional earth knowledge. A large part of the diversity of the know-how, transmitted orally for centuries in the western European countries, was lost when earth construction fell into disuse during the 20th century. The absences of written documents make it necessary to use an archaeological approach to rediscover these processes [186]. To this aim, rational means should be developed for earth heritage analysis.

From an architectural and a historical point of view, this knowledge would enable to follow the evolution and the spread of earth construction processes. From a technical point of view, it would help to rediscover the solutions employed by past builders to overcome obstacles that are still relevant nowadays: influence of soil, geography, geology and climate on construction process choices. Given the absence of suitable methodologies, the goal of this chapter is to explore a rational methodology, based on micromorphology analysis of samples collected in earth heritage buildings, aiming at rediscovering traditional earth construction processes.

A short bibliographical summary of rammed earth construction process is proposed in section 3.2 and a bibliographical analysis of cob construction process is proposed in section 3.3. A micromorphological analysis of a rammed earth farm is proposed in section 3.4 and the micromorphological analysis of a cob building is proposed in section 3.5.

3.2 Vernacular rammed earth process description

Traditional rammed earth process is described as the manufacturing of locally available earth, slightly wet, tamped in a formwork using a wood rammer [66,82,83,187,188]. Steps of this traditional process were earth excavation, preparation and ramming. Since topsoil is unsuitable, for convenient reasons [66,82,83,187], earth was excavated in the layer just below the topsoil [145]. Material supply was made as and when required by the needs of the site work [187]. During material preparation, clods of earth were broken. Earth was gathered in a pile to let coarse elements roll down the pile and to be removed [187]. The obtained bulk earth was placed by layers of 10 to 15 cm inside the shuttering. Each layer was spread by foot, and then tamped thanks to a rammer, with a more or less pointed edge. After compaction rammed earth layers were 6 to 10 cm thick [66]. Once all layers inside a shuttering were compacted, the formwork was moved horizontally to go on with wall construction [66,188]. After completion of a level, called a "lift", the shuttering was moved vertically to carry out a new lift. The ramming effect was more important in the top of a rammed earth layer than in its bottom. Hence, the earth density is higher in the top of the rammed earth layer than in its bottom [189].

3.3 Cob bibliographical analysis

3.3.1 Introduction

Unlike rammed earth, little literature is available on cob and no general description of cob process exists. Hence, the aim of this section is to analyse cob bibliographic data in order to provide a description of vernacular cob construction process.

Among the 133 references used to describe local cob construction techniques, 77 % concerned France and United Kingdom (Table 6). This bibliography is an overview of vernacular cob construction techniques around the world, with a focus on France and United Kingdom.

A large variety of vernacular names for earth construction techniques (Table 7) fall under the definition of cob process. Nowadays, these names tend to disappear in favour of the universal term, "cob". This allows a better international communication between researchers, engineers and professionals of earth construction, but it erases the nuances between local techniques and causes equivalence problems.

Indeed, those names sometimes describe similar techniques and sometimes describe different variations of cob process. For example, *bauge* in Brittany (France) and *mâsse* in Normandy (France) describe the same technique (see case a, section 3.3.3.1), as well as *caillibotis* in Brittany and *gazon* in Normandy also describe the same technique (see case b, section 3.3.3.1).

Table 6. Geographical distribution of cob construction process description in bibliographical references. France and United Kingdom together represent 77 % of the bibliographical references.

Country	Number of citation	References
Afghanistan	3	[80,190,191]
Belgium	1	[192]
Burkina Faso	1	[193]
Czech Republic	3	[148,149,194]
France	59	[16,39,44,73,74,76–79,93,126,127,151,156–158,160–164,174,175,177,195–229]
Germany	4	[12,35,155,159]
Ghana	1	[190]
Hungary	1	[69]
India	3	[80,190,230]
Iran	1	[61]
Ireland	2	[72,231]
Italy	3	[18,232,233]
Ivory Coast	1	[234]
Madagascar	1	[161]
Mali	2	[235,236]
New Zeeland	3	[32,36,237]
Nigeria	2	[118,238]
Senegal	1	[234]
Slovakia	1	[149]
Sudan	1	[190]
Tajikistan	1	[80]
Togo	2	[150,234]
Turkey	1	[69]
Turkmenistan	2	[80,239]
United Kingdom	44	[13,14,17,27,34,59,61,63,65,72,91,115–117,120,121,123,125,152–154,240–262]
United States of America	4	[15,159,237,263]
Yemen	1	[61]

The term *bauge* has been imposed on the entire francophone area instead of regional terms to name this technique [192]. However, the word *bauge*, in its strict meaning, refers to the earth, fibre and water mixture that was traditionally employed in Brittany for earth construction [174,175,177,209,210]. Although this term refers to the mixture obtained, it inevitably refers to its associated process. Nevertheless, using the term *bauge* to name *mâsse* constructions of Normandy is a misnomer and using the term *bauge* to name *caillibotis* or *gazon* technique is confusing.

Table 7. Vernacular names of cob construction process.

Country	Local names	Reference
Afghanistan	pakhsa	[69,80,122,191]
Belgium	tourton	[192]
Czech Republic	nakladani, valek, války	[69,149,194]
East Africa	daga	[69]
France	bauge, bigôt, bouzillage, caillibotis, coque, daube, gachcoul, mâsse, mâssé, mur d'argile, paio-bard, paillebart, paillebort, palho-bard, pâtons de mâssé, terre, torchis	[16,69,75,77,126,207,211,214,216,220,225,229,249,250]
Germany	lagenlehmbau, lehmweller, wellertechnik	[69,155]
Hungary	valgoy	[69]
Iran	chineh	[69,122]
Iraq	tawf	[69]
Ireland	tempered clay	[72]
Italy	atterati , maltone, massone,	[69,264,265]
Madagascar	tamboho, tovam-peta	[69,161]
Portugal	terra empilhada, terra modelada	[69,265]
Spain	chamizo, muro amasado, pared de mano, terra apilado, terra amassado, fang	[69,265]
Slovakia	lepanice, nakladana stavba, vykladanie, valok	[69,148,149]
Sudan	jalous	[190]
Turkey	pahsa	[69]
United Kingdom	clay dab, clay dabbin, clob, clom, cob, dab, daubin, dung wall, korb, mudwall, mud walling, puddled earth, tai clom, tai mwd, tai prid, witchert, wychert	[22,27,34,65,72,117,122,152]
West Africa	banco, banko, terre de bar, swish	[69,190,193]
Yemen	zabour, zabur	[65,69]

To avoid this confusion, it should be specified when *bauge* is used in a strict sense (*bauge s.s.*) to differentiate it from its acceptance as a general term. The same difficulty exists for the internationally accepted term cob [64]. Some authors [66,67,69] proposed to name this technique “piled earth” since it better described this construction process. Nevertheless, it failed, for the moment, to take over from the term cob. As with *bauge*, it should be specified when cob is used in a strict sense (cob s.s., the vernacular technique used by past builders in Devon [13]) to differentiate it from its acceptance as a general term, cob.

A summary of cob construction process is proposed in Figure 22, using the engineering process description: an *engineering process* is divided into a succession of *elementary steps*. Based on literature information, cob process is divided into 4 elementary steps: (1) raw material supply and preparation, (2) mixing, (3) implementation and (4) rectification and drying.

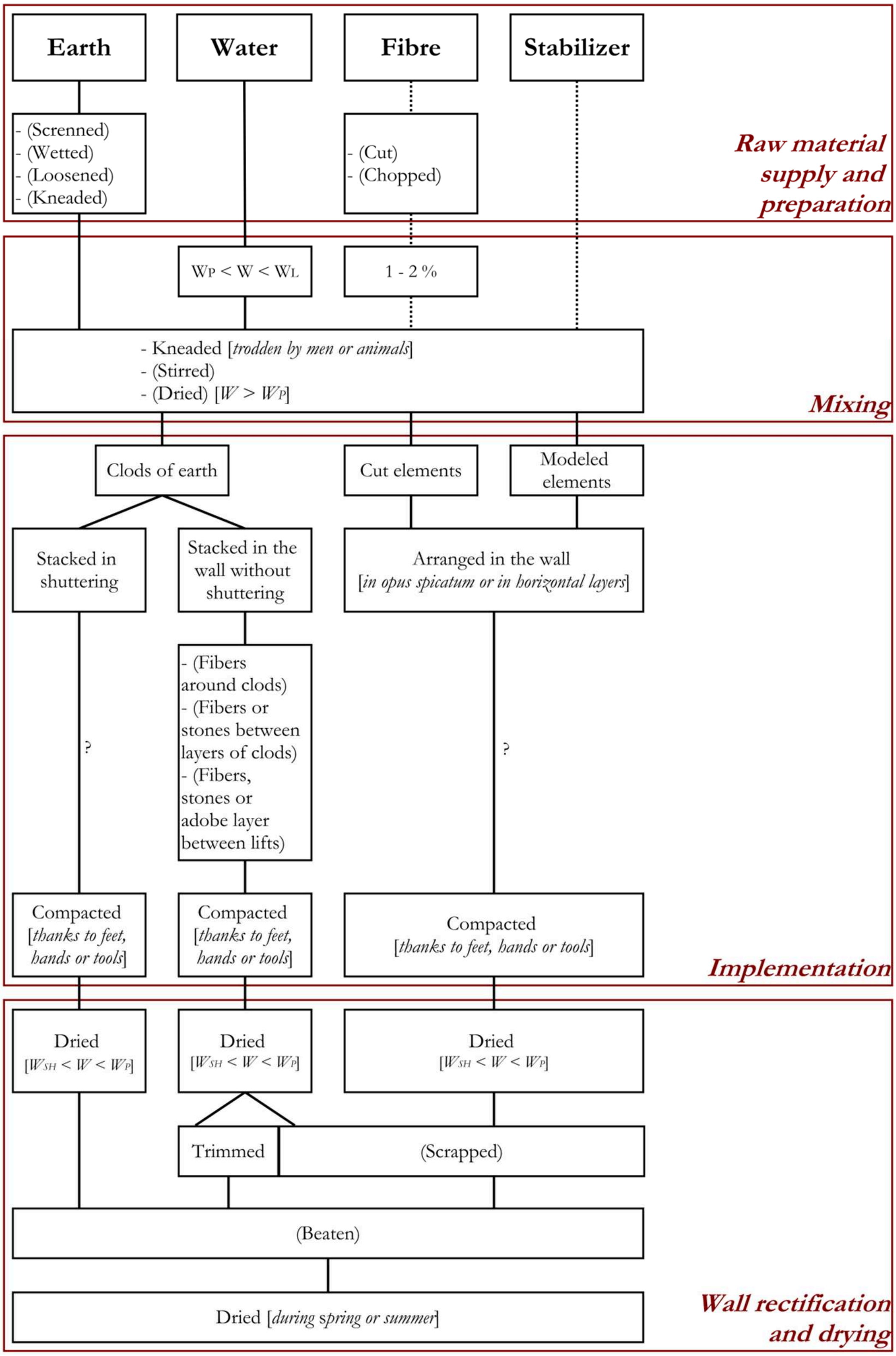


Figure 22. Summary of vernacular cob process. Water contents are to be regarded as order of magnitudes. (elements in brackets are optional; W = water content, WL = water content at liquid limit, WP = water content at plastic limit, WSH = Water content at shrinkage limit).

3.3.2 Material supply

3.3.2.1 Earth

Earth source selection

For past builders, the first step of the cob building process was the identification of a source of earth. Authors agreed with the fact that cob earth material was locally sourced. This was demonstrated by the similarity between available soils next to cob heritage buildings and the earth used in their walls [12,16,91,115,125–127,151,245]. More precisely, locally sourced earth materials meant that they could have been dug from the foundations of the building [164], a pond next to the new building or in a field surrounding the building [77,79,117,127,156,158,160,162,164,174,177,200,209,210,249], inside and immediately around the building during the construction [77,161,209], a field around the building [77,150,156,177,200,210,249], the cellar of the building [72,164], an earth quarry, located in the same borough [126], a ditch cleaning [229] or a hollow way [177,210,227]. Another practice that appears to have been quite common, but difficult to attest, is the reuse of the earth of old cob walls [194,211]. It is then possible to set what "local earth" meant for vernacular cob construction. It was an earth excavated on-site or, tenth [162] or hundredth [174] of meters or, at most, a few kilometres away from the site [126].

Earth excavation and transportation

Topsoil is rich in organic matter that decomposes after implementation and created mechanical weaknesses inside earth walls [18,81,84,89]. It was therefore considered as unsuitable for cob construction [18,22,72,76,77,116,159,162–164,177,196,198,210,211,229,246,266] and it was cleared off before the excavation was carried out [72,177,210,266]. Sometimes topsoil was removed the year before the construction took place, in order to break down the subsoil under the effect of winter moistening and freezing to ease the excavation process [72]. The excavation was done by the owner and relatives [76,116,150,156,174,193,197,200,210,234] by hand, thanks to, for example, a mattock [80].

Because the most suitable earth for construction was found just below the topsoil, excavation concerned a large surface area and a thin layer of soil [77,164]. When not excavated on-site, earth was transported to the site by animal-drawn tumbrel and stored [200,210,216,249,259]. For a 20 m^3 earth lift, this corresponded to 10 tumbrel travels [156].

A unique source of material was sometimes not enough to complete the walls of the building [121]. For example, when the earth excavated from the foundations of the building was not enough, another local material source was exploited (dug from a pond, a field, a hollow way, etc.) depending on needs and opportunities. The use of different earth sources was highlighted by the variations of colour and texture from a lift to another [250].

A first option was to carry out the material supply at once, and all material sources could have been mixed together [72]. A second option was to carry out the material supply separately for each lift [156]. Indeed, the amount of earth necessary to carry out one lift was estimated to 20 m^3, which corresponded to several working days of hard labour for the working team [156].

Sometimes the poor earth quality required to temper it thanks to another material [193,211,216,229,242]. Thus, another source of earth or aggregates could have been employed as an earth grading corrector [72,193,211,229].

Earth preparation

Sometimes, earth was brought on-site the year before the construction took place so that weathering effect broke it down in order to facilitate the screening (if required) and the mixing of the material [12,117,205,229] and to let the organic matter to decompose [229]. If rainfalls were not sufficient, the earth was wetted during winter [229]. More generally, earth was stored close to the building site some weeks before the construction took place [156,211,249]. The preparation of the earth, prior to mixing, could involve one or a combination of the 4 following actions: (1) earth was got rid of large rocks [13,34,61,77,121,151,158,164,177,200,210,242,244,246,249,252], maximum particle size diameters is in the region of 50 mm (Table 8); (2) earth was loosened [13] thanks to a hoe [77,177,200,246], a mattock [252] or a spade [252], in order to break clods of earth; (3) earth was soaked days before mixing to make it more workable and to homogenize water content [47,61,77,80,156,164,177,200,210,249]; (4) earth was trodden by men [249] or by animals [156,205] to prepare soaked earth prior to mixing.

3.3.2.2 Water

As there was no water supply network at the time of their construction, cob buildings were more likely located near water sources [64,247,259]. Water was taken from the well of the farm, from a pond created by the excavation of the earth material [156,229] or from a ditch close to the construction [211,229]. In Brittany, the cob wall construction had to be completed before July, because, as water became scarce in summer, its use was restricted to farm activities [200,210]. In Devon, water supply seemed to have been a less critical problem since cob building took place in late spring and during the summer months because these periods were favourable for wall drying [34,37].

*Table 8. Maximum particle size diameter, fibre type, preparation and length, fibre content (when data are given for 1 m3 of earth, a density of 1600 kg.m-3 for earth has been considered to calculate the fibre content by mass, those calculated fibre content are labelled *) and water content at manufacturing stage (W_m) by weight of cob mixture according to literature.*

Reference	Maximum particle size diameter (mm)	Fibre type	Fibres cut	Fibre length (cm)	Fibre content by weight (%)		W_m (%) by weight
					Minimum	Maximum	
[195]		straw	Yes				
[195]		hay	Yes				
[152]					1.3		
[175]		furze	Yes	10 – 15			
[175]		straw	Yes				
[164]	80 – 100	straw	Yes				
[196]		straw	Yes	15 – 20			
[197]		straw	Yes				
[190]		straw	Yes				
[163]		straw	Yes	15 – 20			
[174]		straw	Yes	15 – 20			
[198]		straw	Yes				
[116]		straw	Yes	40			
[249]		straw	Yes	60			
[200]		straw	Yes	60			
[250]					1.6*		
[61]					0.3*	1.0*	
[156]					1.6*		
[13]	50						
[120]					1.0	2.0	
[252]	50 – 60	straw	Yes				
[204]		straw	Yes				
[253]					1.5	2.0	
[36]		straw	No				
[158]		straw	Yes	15 – 20			
[205]					1.6*		
[254]					2.0		18
[155]		straw	No	70			
[207]		straw	No				
[207]		hay	No				
[159]		straw		40 – 50			
[121]	50						18 – 25
[210]		heather	Yes				
[126]					1.6*		
[115]		straw	Yes				
[22]		straw	No		1.0	1.5	
[14]		straw	Yes				
[151]							10 – 20
[34]	50						18 – 25
[12]		straw	Yes	30 – 60	1.4*	1.8*	
[267]		straw	Yes	30 – 50	1.3*	1.9*	
[118]		straw	Yes				
[268]							15 – 30
Average					1.4	1.7	-

3.3.2.3 Fibres

Although unfibered cob was mentioned [22,34,72,80,150,234,238], cob technique was generally associated with natural fibre addition. Most commonly cited fibre employed for cob is straw (Table 9). According to Petitjean [210], during the 19th Century, the evolution of agricultural practices generated straw excess, fostering its use at the expense of fibres used before. Actually, large varieties of fibres were used in vernacular cob construction (Table 9). Since fibres were locally sourced [37,162], this diversity reflects the adaptations of the vernacular cob construction process by past builders to resources available in their nearby environment. Authors both referred to cut, or chopped, and uncut fibres (Table 8). Two modes for fibre length can be identified (Table 8): (1) small fibres (10-20 cm), fibres length being about equal to the size of a cob clod, (2) long fibres (40-60 cm), fibres length being about equal to the width of the wall.

The role of fibres inside cob walls was to (1) facilitate the mixing [34,72,120], (2) assist handling [12,13,16,22,117,120,150,198,209,234], (3) accelerate the drying process [22,34,37,72,77,120,209], (4) distribute shrinkage cracks throughout the wall mass [13,17,18,22,34,37,72,80,117,120,191,209,250,269], (5) enhance cohesion and shear resistance of the wall [13,16,17,22,34,37,120,155,209,269,270], (6) improve weathering resistance [12,120,270], (7) reinforce bond between lifts [198,229] and (8) wall angles [161,229].

Some authors [34,37,155] stated that fibres contributed to the thermal insulation of the wall. Yet, Keefe [22] argued that thermal conductivity reduction of a cob wall was significant only if a lot of fibres were added to the mixture (about 25 % by mass). The fibre content of cob was generally between 1 to 2 % by mass (Table 8). In this case, the thermal contribution of fibres seemed very limited. Anyway, the most important function of fibre is thought to be the distribution of shrinkage cracks [22,34,72,250].

3.3.2.4 Stabilizer

Fibres can be regarded as a stabilizer. As most of the vernacular cob was fibered, it might not necessitate further stabilizer addition. As a consequence, the use of cement or lime as a stabilizer in cob mixture seemed to have been rarely employed [13,72,118,150,244]. Keefe [22] considered hydraulic binder stabilization with a critical eye. According to him, under temperate climate, it should be possible to construct strong, durable buildings without recourse to stabilization. Moreover, he stated that during this process, the soil undergoes a fundamental and irreversible chemical change so that it is no longer recyclable, becoming, in effect, a sort of "brown concrete" [22].

The use of natural stabilizers was mentioned in the literature: animal dung, small pieces of straw, chalk, vegetal oils, white of egg, cow urine, ashes, milk, blood, buttermilk and casein [13,72,150,161,190,261]. Too little information is available about stabilization in cob literature, thus, the use of stabilizer is not detailed in this section.

Table 9. Number of citation and bibliographical references of different fibre type employed with cob.

Fibre	Number of citation	References
animal hair	4	[34,72,156,205]
barley straw	8	[13,34,72,115,117,163,196,252]
bean pod	2	[164,174]
broom	5	[77,117,126,162,210]
cow parsley	2	[34,72]
fern	5	[16,78,117,162,250]
flax	3	[34,37,72]
furze	11	[16,34,72,76,162,164,175,197,200,210,229]
grass	6	[34,72,126,156,200,250]
hay	22	[13,16,34,72,77,78,117,126,156,164,174,175,195,200,205,207,209–211,216,225,250]
heather	18	[34,37,72,74,76–79,117,162,164,174,175,197,200,210,250,261]
leaf	1	[234]
moss	2	[34,72]
needle	1	[229]
oakum	3	[164,174,175]
oat straw	12	[16,34,37,47,72,157,164,174,175,197,200,210]
quack grass	2	[34,72]
reed	2	[37,72]
rice straw	2	[47,235]
root	1	[234]
rush	8	[16,34,117,126,156,164,205,250]
rye straw	7	[12,37,47,77,155,209,210]
sedge	5	[34,72,211,216,229]
straw	47	[15,17,18,22,27,32,36,61,76–79,117,120,126,149,150,152,153,158,162,164,174,175,177,190,191,195,197,198,207,209–211,216,225,229,234,235,242,246,249,250,253,254,263,264]
stubble	2	[152,160]
twig	6	[13,34,72,77,209,250]
vine shoot	1	[74]
wheat straw	13	[12,13,16,34,37,47,115,116,155,157,163,200,252]

3.3.2.5 Mixing

When raw materials (earth, water and, if required, fibres and supplementary earth or aggregates) were supplied on site and prepared as described in section 3.3.2, they were ready to be mixed together to form the cob mixture. Mixing took place on a flat and if possible hard [13,242] and impervious [252] surface. This surface was sometimes pre-wetted [13,252] and sometimes covered with a bed of fibres [13]. Earth was spread on this surface and arranged in the shape of a flat circular heap (1 to 6 m diameter) next to the wall under construction [115,242,244,246], or in a continuous pile of earth (0.5 to 1.8 m large) all around the future building, alongside the walls under construction [156,177,200,210,249]. More rarely the mixing was done in a rough trough [244].

Earth was spread to form a layer some centimetres thick [200,210,249] to 10 cm thick [13,196,246]. Fibres (when required) were evenly distributed on the earth [12,13,115,156,158,177,196,200,210,244,246,249,252] and the whole was trodden by men [12,13,22,32,61,72,76,77,80,149,150,153,154,157,158,162,164,174,175,177,190,191,196,200,210,211,216,229,230,234,244,246,249,250,252,271] or by animals [13,16,61,72,76,77,149,162,177,191,200,210,271], generally horses [77,115,152,154,156,205,242] or oxen [77,115,154,211,216,229]. During mixing, more fibres (when required) were gradually added [115,175,216,242] and water content was corrected, based on guesstimate of the cob masons [12,13,22,34,80,115,196,242,252]. Water content of manufacturing stage of the cob mixture should bring it into a workable mix [13,61,151,152], i.e. into a plastic state [12,16,77,156,163,191,224,267]. Water contents of manufacturing stage are in the region of 20 % (Table 8), which is in agreement with a plastic state. Average fibre content range from 1.4 to 1.7 % by mass (Table 8). This is in agreement with the optimum fibre content around 1% proposed by Danso et al. [270].

In order to ease the mixing, some authors referred to the use of forks [72,216,229,242], picks [115,244] and hoes [76,234,271] to stir the cob mixture [13,22]. When the mixing of the first layer was completed, the process was repeated several times to carry out other layers over the first one [156,196,246] in order to create a pile of earth 60 to 100 cm thick [156,246] . The treading could last 1 to 2 hours [205], a half-day [234] and up to 3 days [230]. Cob mixture is ready to be placed inside the wall, but it could have been let to dry overnight up to a few days before to be used [16,191,196,234,250,252].

The purpose of cob mixing is to evenly distribute clay, water and, if added, fibres in the cob mixture in order to maximise the contact surface between wet clays and other constituents of the cob mixture [12,13,22,34,47,120,252]. Indeed, as it has already been demonstrated for other earth construction materials, cohesion is provided by capillary forces of water menisci attached to clay particles [31,70,272–274]. Thus, mechanical strength and durability is enhanced if clay particles are evenly distributed inside the earth matrix [22,70,120]. Soils are usually organised in peds [89]. In order to evenly distribute clay particles inside earth material, it is then necessary to break those peds to mobilize clay [22,252]. For wet earth construction techniques, this is achieved thanks to kneading action of soaked earth, water playing the role of a dispersing agent. Dispersing action of water is efficient if water is well distributed and in sufficient amount inside earth material. Cob mixing is easier and more efficient if earth was pre-soaked and mixed in a wetter, more humid plastic state [12,22,34,36,61,120,252].

Besides kneading action, blending action of the mixing process allowed an even distribution of the constituent of the mixture [22,47,120,252]. Indeed, inhomogeneity would create weak points inside cob walls [252]. This was even more essential when another constituent was added to the cob mixture (sand, stones, fibres, etc.). Fibres provided extra tensile-strength to cob walls and improved weathering resistance

[12,13,16,17,22,34,37,120,152,155,209] but this was only true if fibres were evenly distributed [36,120].

3.3.3 Wall construction

3.3.3.1 Earth elements implementation

Cob walls were made by the stacking of: (a) clods of earth snatched from the cob mixture pile, (b) plastic elements of earth cut in squares, (c) plastic elements of earth modelled by hand into specific shapes, or (d) wet clods of earth snatched from the cob mixture pile inside a shuttering.

In case (a), which was the most widespread vernacular cob construction techniques, material was taken from the cob pile next to the wall with a fork, with hands or with a shovel by a workman and given to the skilled craftsman, standing on the wall, who arranged the clods of earth: a first one was placed on one side of the wall, a second one on the other side of the wall and a third one in the centre, ensuring that they correctly overlapped each other in order to provide sufficient cohesion between elements [12,13,16,22,34,37,65,74,76–78,116,126,152,153,156,159,174,177,190,191,197,198,200,205,210,211,229,230,237,242,244,246,249,250,275]. Clods of earth were disposed so that they overhung the plinth on both sides of the wall by 5 to 15 cm [13,34,77,116,126,152,156,159,177,200,205,244,246,250,275]. Clods were often arranged in diagonal layers [13,16,152,194,244,246], by, for example, an angle of 35 – 45° [16,194]. Sometimes fibres were placed around each clod [78,209,224] or between each 6 to 8 cm layer of clods [16,76–78,117,174,198,224]. The use of wood dowel between each clod [229] and the use of bed of stones and/or tiles between each layer of clods [16,229] was also mentioned. Once in the wall, clods of earth were compacted by the trampling of the craftsman who worked on the wall [13,14,27,34,65,78,115,120,122,152,153,244], by hand [61,150,190] and/or with a tool (fork, stick) [12–14,34,78,120,122,152,156,250]. As the cob mixture was implemented in a plastic state, the material subsided under its own weight and tended to overflow. During the construction, sides of the wall were then regularly beaten with a stick, feet or a fork to tighten the faces of the wall [34,77,126,177,200,209,210,242,246,250].

In the United Kingdom, several authors referred to a “quick process” by opposition to a “slow process” [14,22,117,276]. The “slow process” is the technique described above, i.e. stacking of clods of earth in a lift, left to dry for several days or weeks before another lift could be implemented on it. The “quick process” consisted in stacking clods of earth in small courses (around 8 cm) separated by a layer of straw in a continuous way through the completion of the wall. According to McCann [117], walls were completed in 1 day thanks to the “quick process”. In this technique, fibre layers should have played a significant structural role at fresh state.

In case (b) the cob mixture was spread on the ground in a 10 cm thick layer [205] and cut in squares of 20-25 by 25-30 cm [77,190,250] with a sharp tool. These small rectangular blocks of cob could have been left to slightly dry before they were placed inside the wall [16]. They were then arranged in the wall in horizontal layers or in *opus spicatum* [16,76–78,164,174,190,205]. This technique is called g*azon* or *pâtons de mâssé* in Normandy [16,47,205,250] and c*aillibotis* in Brittany [77].

In case (c) the cob mixture was modelled by hand in a specific shape [148,149,194] (cylinder, ball, cigar, triangle) before to be stacked and compacted on the wall. *Massone* in Italy [18,232,264] and *Banco* in Africa [150,159,234,236] are some examples of this kind of technique. In Italy, unfibered cob mixture was modelled in the shape of cylinders called *massone* (8 – 15 cm in diameter and 30 – 40 cm long), rolled and covered with straw before they were implemented on the wall [18].

For case (d), several authors referred to the use of shuttering for cob wall construction [13,22,117,148,152,156,157,164,194,244]. This technique was called shuttered cob or puddled earth [22,72,117,152]. For example, shuttered cob is attested in Devon from around 1820 right up to 1914 [13,22]. According to Keefe [22], shuttered cob mixture is wetter than unshuttered one. Thus, in this case, drying times were long.

3.3.3.2 Lift subsidence

Since cob was implemented at plastic state, its mechanical resistance was low and the material subsided under its own weight during the construction process. The height of wall done at one time was limited. As a result, cob walls were a superimposition of successive monolithic earth raised, called lifts. A new lift was performed when the previous one was dry enough to bear the weight of the new lift without deforming [14,27,80,152,154,230,242]. The height of a lift varied with soil type, plasticity and stress applied on the wall during construction. Lift heights ranged from 10 to 120 cm with an average of 59 cm (Figure 23). Wall thicknesses ranged from 10 to 150 cm with an average of 62 cm (Figure 23). In the 17th century and earlier, wall thicknesses ranged from 80 to 90 cm or more [76,117,177,244]. It decreased to 50 to 60 cm in the 18th century [22,117] and reached 50-45 cm during the 19th century [22,177]. With time and improvement of the technique, craftsman were more and more confident and built thinner walls [12,13,22,34,76,77,80,117,177,244,245]. Slenderness ratio ranged from 0.5 to 1.6 with an average of 1.0 and a standard deviation of 0.3 (Figure 24). Slenderness ratio of lifts is proposed as an indicator of the convenience of earth and of associated process variation, the higher the slenderness and the better the convenience. Four classes of slenderness are defined for cob lifts (Figure 24).

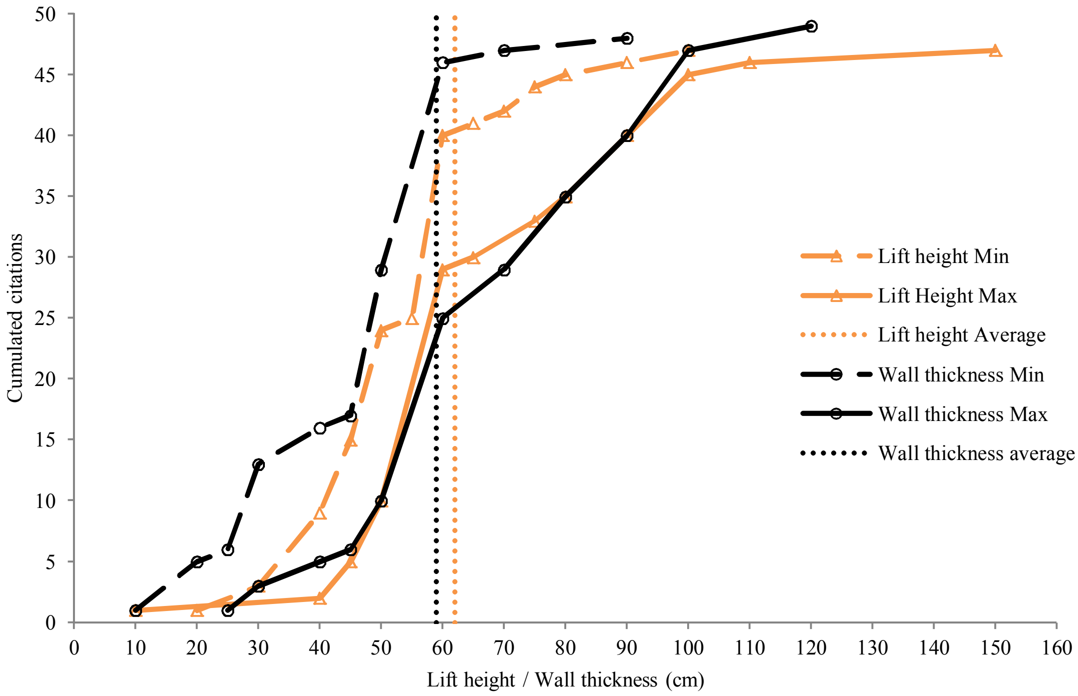


Figure 23. Cumulated citations of minimum (Min) maximum (Max) and average values of cob lift height and cob wall thickness.

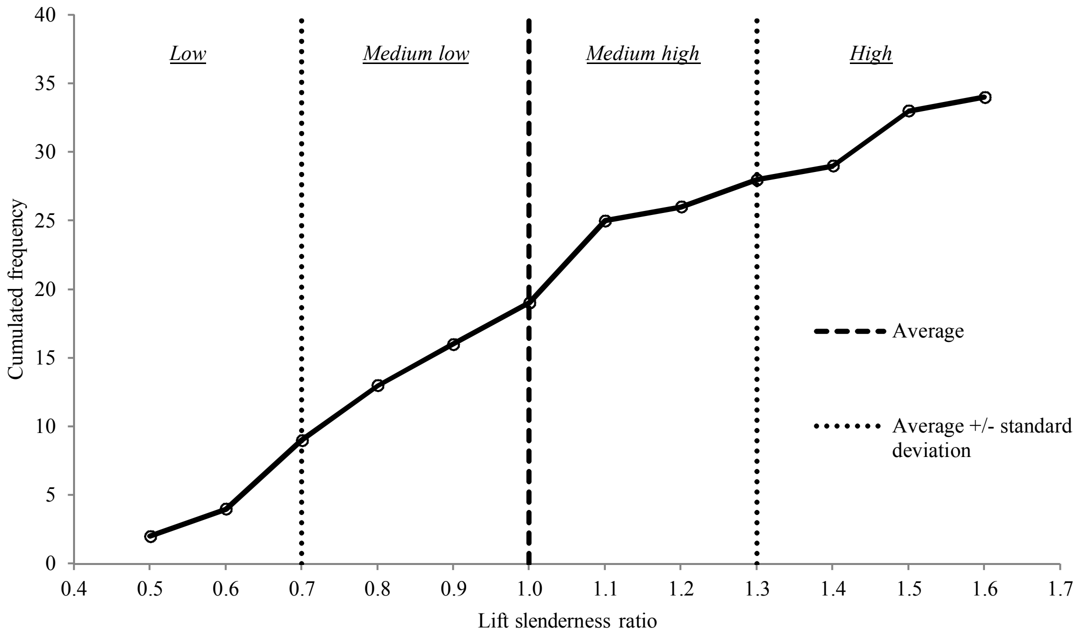


Figure 24. Cumulated frequency of lifts slenderness ratio together with average slenderness ratio (1.0 with standard deviation of 0.3) and average +/- standard deviation. Slenderness ratio are divided into 4 classes : Low (< 0.7), Medium low (0.7 – 1.0), Medium high (1.0 – 1.3) and High (> 1.3).

Earth consistency depended on its clay content, which differs naturally from one soil to another, and its water content, which was determined by the cob Mason, according to his building practices [13,16,22,36,80,252]. To carry out higher lifts and save time, clods of earth with a firm consistency were preferred, i.e. on the "dry side" of the plastic state [22,34,120,252]. This is in contradiction with the optimal mixing water content suggested in section 3.3.2.5 ("wet side" of the plastic state). Several strategies have been employed to overcome this problem: some masons used a drier mix, which required higher kneading force or longer kneading action, some let cob mixture to dry before implementation and others used shuttering to ease the placing of the wet mixture inside the wall [34,61,120].

Fibres were employed to assist handling of clods and provide extra strength to fresh cob lifts and therefore built higher lifts [12,13,16,22,117,120,150,198,209,234]. The higher the water content was and the higher the fibre content should be. This relationship was illustrated by Saxton [120].

3.3.3.3 Faces rectification

Another consequence of the sagging of cob lifts was the bulging of the material over the face of the plinth, creating an excess of material. Thus, faces of the wall had to be rectified [14,77,115,122,151,152,154,159,191,224,252]. This operation could have involved one or a combination of the three following actions: (1) trimming thanks to a special flat, sharp edged spade called "paring iron" [13,16,27,61,65,74,76,78,80,126,156,177,200,205,210,218,244,246,250,268,271,275] and sometimes a fork [77,116,174,216,218,229], a mattock [13], an adze [27,275], a saw [16,275], a shovel [17], a knife [61] or an axe [149]; (2) beating the faces of the wall thanks to a stick [16,61,74,77,78,126,156,205,209,227], hands [61,80], mallet [16] or stone [61] ; (3) scraping [224] overflowing material thanks to a fork [74,78,196,198] or a garden claw tool [74,78].

In case (a) (section 3.3.3.1), cob was implemented in order to overhang the plinth of the wall creating a significant excess of material that has to be trimmed or scraped. This operation was carried on when the cob material was quite dry to avoid bulging of the lift but not too dry to ease the process [116,275]. Depending on the weather, it took place few days up to 3 weeks after the achievement of the lift [13,14,16,27,74,77,116,156,191,205].

The most cited trimming technique is the use of the paring iron. The trimming with the paring iron smoothed the faces of the wall unless cob material contained oversized stones. In this case, the paring iron edge pushed oversized stones down, creating vertically elongated cavities called *cheminées* (chimneys) in France [77,200,210]. This was one reason why large stones were removed from earth (section 3.3.2.1). Another imprint left by the paring iron is the downward orientation of fibres [74].

The faces of the walls were beaten in order to rectify the shape of the lift, to get the gravels inside the walls, to fold fibres down into the walls and to close the drying shrinkage cracks [77,126,156,205,209]. The beating of the faces of the cob lift could be performed before and/or after trimming and all along the drying period [77,126,156,205].

An example of an elaborate lift face rectification was provided by Bardel and Maillard [77]: the faces were trimmed thanks to a first specific paring iron, beaten and left to dry for 4 days before they were definitively trimmed thanks to a second specific paring iron.

For the cases b, c and d, it was usually not necessary to trim the cob lift, but the faces of the walls were generally rectified by beating actions [16,77,205].

When unrendered, the faces of the wall could have been smoothed by a trowel, hand or plaster float [156,193,224,229,230]. When rendered, faces of the wall could have been finger-marked in order to provide roughness and a better key for the plaster [229]. Rectification process determined the final shape of the wall. It could have been straight [161] or tapered [16,61,74,78,80,116,126,156,196,229,250,264] to provide more stability to the wall.

3.3.4 Drying

3.3.4.1 Drying duration

Average drying times of a cob lift ranged from 11 to 21 days (Figure 25), depending on climate [16,17,22,61,74,77,80,116,151,156,163,174,177,196,200,234,242,244,249,250]. Then, the estimated time necessary to achieve cob walls, excluding "quick process" (section 3.3.3.1), ranged from 3 to 20 weeks [117,154,190,244,249,250].

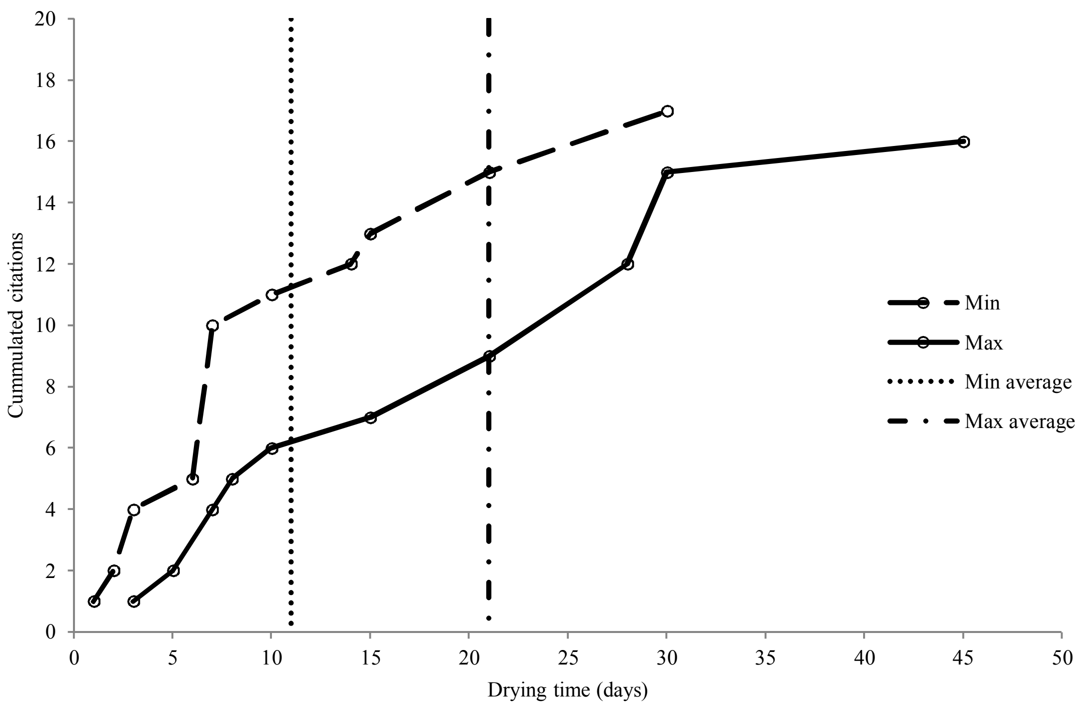


Figure 25. Cumulated citations of minimum (Min) and maximum (Max) drying time of cob lifts, together with calculated average minimum drying time (Min average) and average maximum drying time (Max average) of cob lifts.

Drying of lifts was a major time constraint of cob process. Drying was only possible during hot months of the year, thus imposing a "season of cob" [34,37,72,74,77,154,200,205,209,210,244]. The implementation of cob on "dry side" of plastic state could accelerate the drying process. It was also suggested that fibres played a role in easing drying by channelling water from the core of the wall to its outer face [22,34,37,72,77,120,209]. Anyhow, cob walls had to be dried before the first frost to avoid damages [229].

3.3.4.2 Shrinkage

As the cob material dried, it shrunk and shrinkage cracks could expand inside the lift. If this expansion was too large, this could lead to structural damages. Shrinkage rates depended on clay content and water content of manufacturing stage of cob mixtures, high clay content and high water content of manufacturing stage leading to high shrinkage rate [22,120,252]. Several strategies were employed by past cob masons to restrain shrinkage effect. Drying first concerned faces of lifts where shrinkage cracks were initiated. This was the reason why faces of lifts were rectified, by beating the faces in order to close shrinkage cracks and/or by trimming excess cob material in order to cut the shrunk outer part of lifts (section 3.3.3.3).

Another strategy was to use a cob mixture constituent as "shrinkage crack barriers". This constituent could have already been present in the natural soil (gravels) or added on purpose (gravels, sand, fibres, branches, wood pieces, adobes) and it could have been evenly distributed or arranged in a specific manner (Figure 26). Layers of fibre, of stone or a course of adobe laid inside or between each lift [22,74,79,80,191] can be interpreted as "shrinkage cracks barriers" [80,191] (Figure 26). The aim of those barriers was to stop the expansion of shrinkage cracks thus avoiding their coalescence and therefore the development of large cracks [13,22].

This distribution of shrinkage cracks throughout the wall mass is well documented for fibres [13,17,22,34,37,72,80,117,120,191,209,250,269]. The tensile strength of fibres embedded in the cob matrix is a supplementary factor that participated to the resistance to crack opening [22,120,269,277,278]. When enough gravel was present in the earth material to contain shrinkage cracks, fibre addition was not necessary [77].

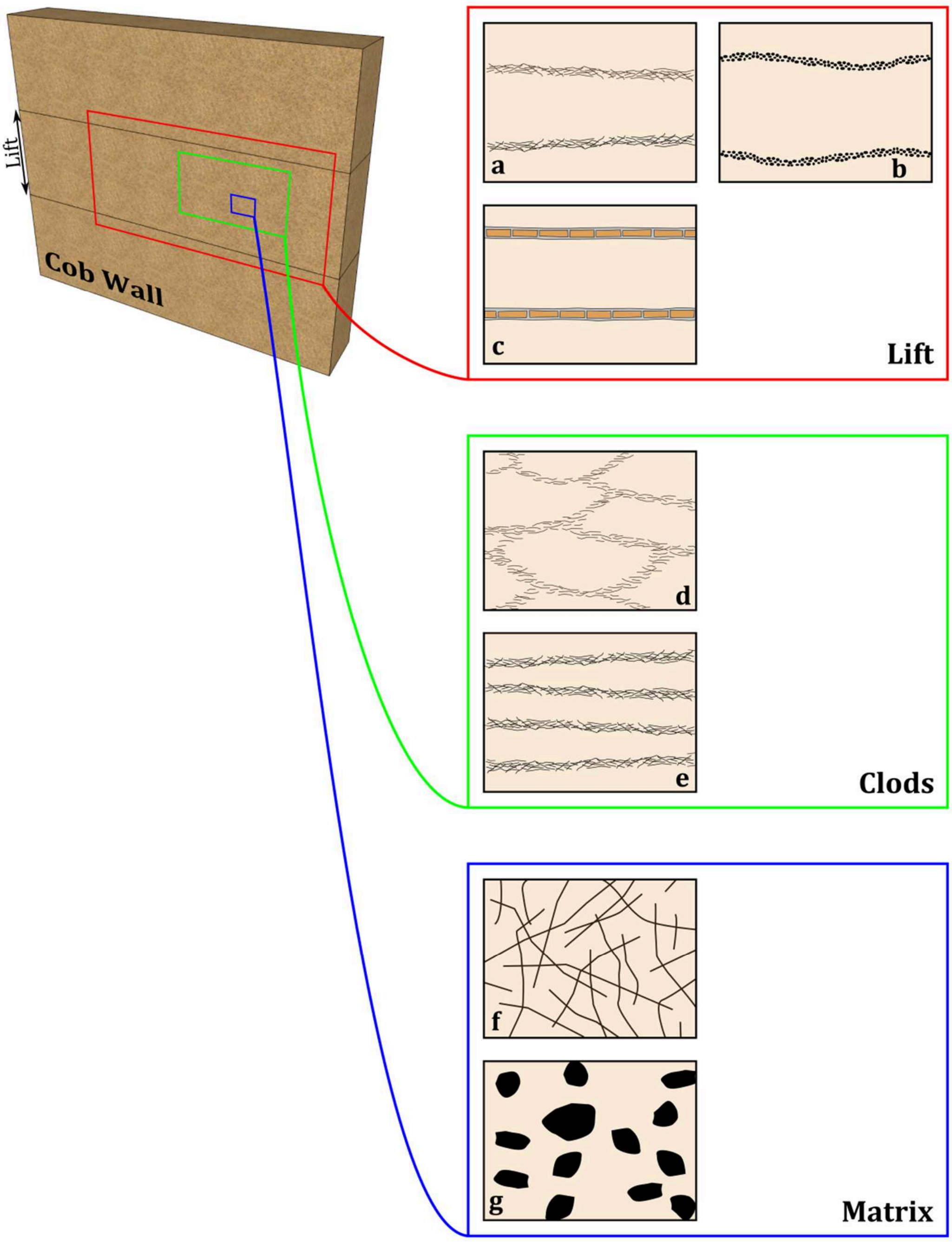


Figure 26. Crack shrinkage barriers placed between lifts (a: layer of fibre or wood, b: layer of stones, c: layer of adobe), between clods of earth (d: between each clod, e: between each layer of clods) or inside the matrix (f: fibres, g: gravels).

3.3.5 Cob bibliographical analysis – synthesis

Better describing and understanding cob technique will permit an appropriate care and repair of cob heritage buildings and consider its application in the field of modern sustainable building. Cob is one of the less studied load-bearing earth construction technique, whereas its large widespread demonstrated its adaptation to different soil natures, climates and social needs across the world.

Moreover, since raw materials were natural and locally sourced, cob masons had to do with available materials. Earth type was the major constraint that dictated construction strategy. The variety of strategies employed by past cob masons at each stage of cob process is illustrated in section 3.3 and it is possible to estimate that, at least, hundreds of variations existed for this process. This diversity is a key to promote the use of locally available and unprocessed construction materials, as it broadens the range of sustainable construction solutions and therefore the possibility to find a sustainable construction process adapted to a local context.

Cob masons expertise was orally transmitted. Therefore little literature exists on the description of cob vernacular process. To go further on the description of earth construction processes, it is necessary to describe and analyse existing heritage buildings. Scientific methods should be developed to go on with this rediscovering movement. This is the aim of sections 3.4 for rammed earth and 3.5 for cob.

3.4 Micromorphological analysis of a rammed earth building

3.4.1 Materials, methods and results

Section 3.4 goes on with the study of the rammed earth barn of Cras-sur-Reyssouze (France) presented in Chapter 2 (section 2.3). Section 2.3 focused on the analysis of pedofeatures deriving from the original soil in place in order to identify the material source. In this section, analysis focuses on pedofeatures inherited from implementation in order to describe the construction process.

The study area was presented in section 2.3.2.1, sampling and thin section production in section 2.3.2.3 and results in section 2.3.3.

3.4.2 Material preparation

Pedofeatures resulting from the mixing and its intensity are described in the literature [130,132,133]. Mixing induces a homogeneous distribution of the coarse fraction in the micromass and the presence of rounded residual aggregates. Here, the material of the wall does not display any characteristic of a mixing action (Figure 9 l). Thus, the material has undergone, at most, a coarse mixing related to the handling of the earth during excavation, transportation and preparation.

Type 1 porosities (section 2.3.3.2) contain Enchytraeids excretions and vegetal debris indicating their root decomposition origin (Figure 9d). Irregular aggregates inside these voids underline the mechanical alteration of void walls and therefore, their aging. The preservation of type 1 porosities, despite the significant compaction of the adjacent earth, strongly suggests that the decomposition occurred after the implementation of the earth in the wall. Type 2 porosities (section 2.3.3.2) are of physical origin (Figure 9e). Type 2 porosities are mainly generated during the modifications engendered by rammed earth processing. Shape and roughness of their walls depend on the water content of the material during their creation, i.e. during excavation and implementation of the earth [139]. Micromorphological characteristics resulting from preparation and implementation of the earth material, relative to water content at the fabrication time, for plastic to liquid state, are described by [133] and summarized in Table 10. Type 2 porosities have rough and irregular walls (Figure 9e). This sort of porosity, combined with the absence of pedofeatures associated to plastic to liquid state, suggest an implementation at solid state. These pedofeatures, significant of an implementation of the material at a relatively dry state, have never been depicted in the context of construction materials. This observation is in accordance with the hydric state of the earth for rammed earth construction, typically under the plastic limit [70,279–281].

Table 10. Micromorphological indicators of the water content of manufacturing stage, after[133].

Pedofeatures	Water content	
	Solid state	Liquid state
Mud intercalation frequency	-	+
Desilting area frequency	-	+
Vesicle frequency	-	+
Cavity roughness	+	-
Cavity sinuosity	+	-

3.4.3 Material implementation

The continuous sand particles alignments combined with horizontally elongated voids separate five horizontal layers (Figure 10). In each layer, porosity gradually evolves from a more porous region, at the base, to a less porous region, on the top (Figure 10). Layer edges are underlined by an abrupt change from a closed porosity below and a more open porosity above. Sharp limits are interpreted as limits of material brings, resulting on the addition of a new earth layer. Sand beds associated with horizontal voids located on layers' top are interpreted as the result of vertical tamping that reduces the volume of bulk earth, flatten voids and create horizontal alignments of sand particles. The inside layer porosity evolution is interpreted as the indicator of the degree of compaction. The upper portion of a layer is more compacted than the lower portion [282]. The superimposition of layers is responsible for the porosity contrast between sharp limits. The estimated rammed earth layers thicknesses vary between 3 and 9 cm (Figure 10). Literature refers to thickness values ranging from 6 to 10 cm for traditional rammed earth [66,282]. Even if some layers can be regarded as thin (L2 and L4, Figure 10), layer thicknesses are in agreement with the literature values. The fineness of the earth employed for the construction did not enable us to distinguish on site the different layers with the unaided eye. Only the micromorphological study permits this distinction.

Inside the layers, discontinuous sand alignments and flattened voids are observed. They correspond to the fabric of type 2 (Figure 9f, 8g, 8h and 8i). Occasionally, subvertical particles and voids alignments change direction downwards and get connected to a subhorizontal alignment, forming a corner shape figure (Figure 9i). Some alignments are highly visible, others are more indistinct. The horizontal particles alignments and flattened voids are the results of a vertical shortening. The tilted and subvertical sand alignments are interpreted as shear lines, a phenomenon compatible with the vertical shortening. The overlap of most of these deformation figures demonstrates the repetition of stresses undergone by the material, which superimpose strains on each other. The repetition of these strains across all layers generates a significant shortening, which is possible only with earth at bulk state. These figures accommodate localised vertical strains, repeated throughout the rammed earth layers. These figures are interpreted as the result of the craftsman compaction of the earth inside the formwork by treading it with his clogs and tamping it thanks to a rammer. The discontinuous sand particles alignments and oriented voids are therefore characteristic of the mechanical tamp undergone by the material at bulk state and are associated with the rammed earth process.

3.4.4 Identification of rammed earth layers thanks to thin section image analysis

3.4.4.1 Introduction

Micromorphological analysis of thin sections of rammed earth has permitted to determine 3 criteria for rammed earth layers identification: (1) abrupt change, from bottom to top, between a low porosity layer to a high porosity layer; (2) subhorizontal sand alignments along the limit; and (3) horizontally flattened voids along the limit. These limits are difficult to follow by naked eye. The aim of this study is to evaluate image analysis technique for rammed earth layers identification.

Subhorizontal sand alignments and horizontally flattened voids are discontinuous along rammed earth layers limits. Hence the image analysis focuses on porosity contrast for layer limit identification. In Plan Polarized Light (PPL) voids can be differentiated from the silt/clay matrix but not from sand fraction (Figure 27). In Cross Polarized Light (XPL), according to their extinction angle, most of the quartz minerals are bright and can be differentiated from voids and clay/silt matrix, but the contrast between voids and clay/silt matrix is not enough (Figure 27). It is proposed to combine PPL and XPL images of thin sections in order to assess pore spatial distribution inside thin sections and therefore to identify rammed earth layers.

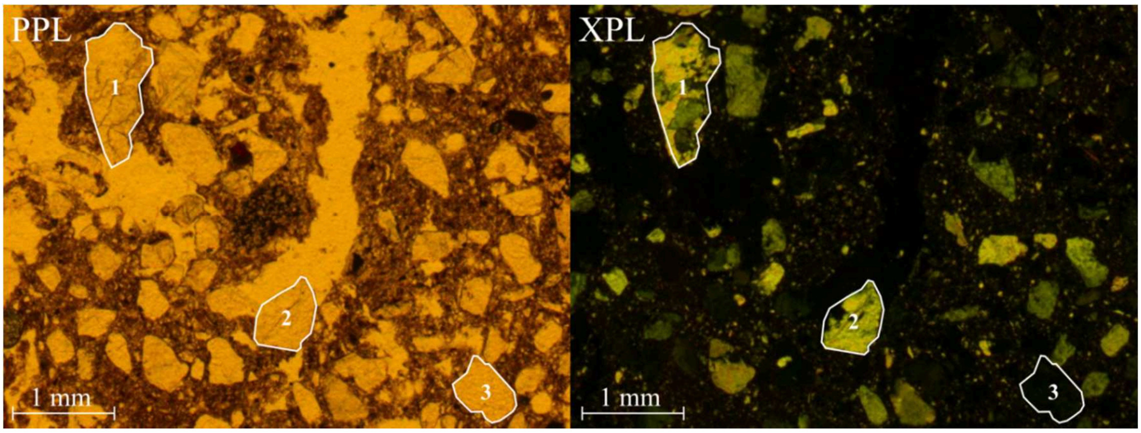


Figure 27. Thin section thumbnail in PPL and XPL with three quartz minerals at different extinction angle.

3.4.4.2 Method

Thin sections were digitalised using a microscope with motorized stage Leica DM5500B and a Leica DFC400 camera, belonging to the AgroParisTech/UMR ECOSYS laboratory. This device records hundreds of thumbnails in order to build high-resolution images of thin sections [283]. Image acquisition was performed firstly in Plan Polarized Light (PPL) and secondly in Cross Polarized Light (XPL) with a 2.5 magnification, corresponding to a 5.3µm.px^{-1} resolution.

Image processing was performed with Fiji software [284]. Image processing is illustrated in Figure 28 and detailed in Appendix B. PPL and XPL thin section images were converted to grey scale and XPL image was inverted [283]. The contrast between voids and quartz minerals of thin sections was not enough to permit a good separation. To increase this contrast, the PPL and the XPL images were combined thanks to an addition with the 'Calculator Plus' of Fiji software. The combined image was scaled (1 px = 5.3 µm), rotated (if necessary) and cropped to eliminate the image area without earth material. The image was then smoothed thanks to a median filter. A threshold was applied to get a binary image of voids. Maximum threshold was set to 255 and minimum threshold was manually decreased, starting from 255, until voids were clearly visible but before quartz were clearly visible. The minimum threshold for all thin sections was set to 230 for this study. The threshold image was cleaned thanks to erosion and dilatation. Finally, all particles were analysed and results were recorded in a text file.

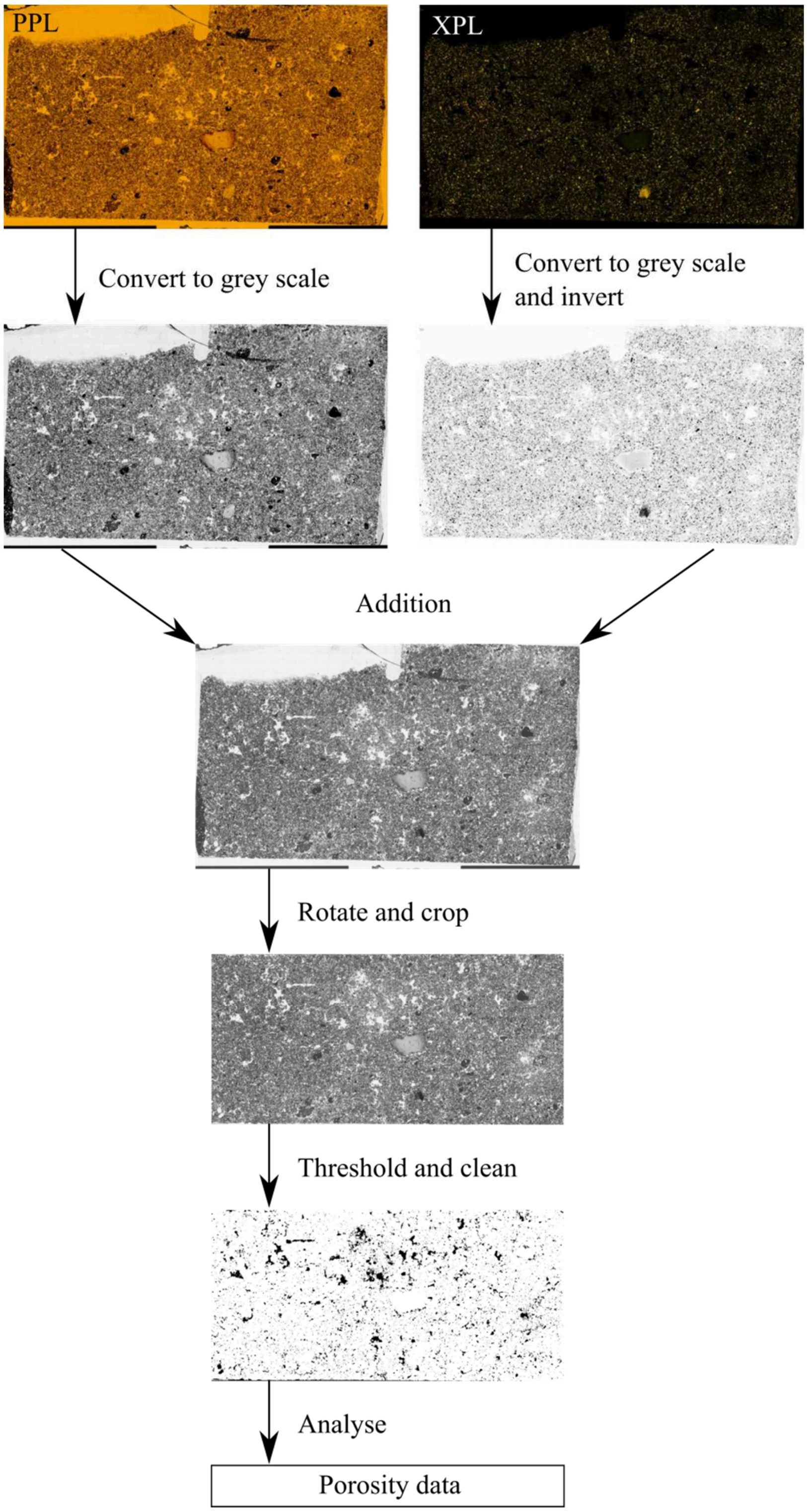


Figure 28. Processing of PPL and XPL thin section images

Results were analysed with Python to draw porosity maps of thin sections. Thin sections were divided into squares of 2000×2000 pixels and porosity was calculated for each square as the surface of voids divided by the total surface and porosity maps of thin section were drawn. Rammed earth layers were continuous, subhorizontally oriented and characterized by an abrupt change, from bottom to top, between a low porosity layer to a high porosity layer. The aim of porosity map analysis is the identification of subhorizontal limits characterized by a porosity contrast in order to try to identify these layers.

3.4.4.3 Results and discussion

The image processing for porosity binarization was assessed on several thumbnails. An example is provided in Figure 29. The addition of PPL and XPL images produced an image with a lower contrast between silt/clay matrix and voids, but contrast was enough to differentiate porosity from the matrix. The addition increased the contrast between most quartz minerals and voids (quartz 1 and 2, Figure 27 and Figure 29). Some quartz minerals were at extinction angle on XPL image (quartz 3, Figure 27) so that their contrast with voids was not accentuated in the addition image. However, unlike voids, quartz minerals have a rough texture. By setting a high minimum threshold for binarization, the smooth texture of voids eased their identification, whereas the rough texture of quartz generated discontinuous dotted shapes (quartz 3, Figure 29). The cleaning of the binarized image, thanks to an erosion and dilatation process, also reduced the size of these discontinuous shapes. Thanks to this image processing, the bias linked to the contribution of quartz minerals with porosity were very limited and pore spatial distribution of thin sections could be therefore regarded as satisfactory.

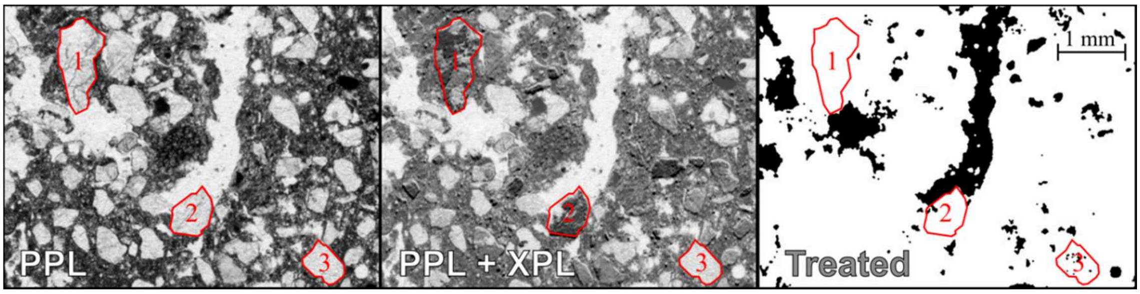


Figure 29. Result of image processing on a thin section thumbnail. Three different quartz minerals (1, 2 and 3) are outlined.

A detail of a rammed earth layer limit of CRA4b was used to assess the rammed earth layer limit identification thanks to porosity maps (Figure 30). Rammed earth limit could be clearly identified on porosity map and results were in agreement with the limit identified by naked eye. Criteria to consider for limit identification in porosity map are (1) an increase of porosity, from bottom to top along a (2) continuous and (3) subhorizontal line. These criteria were applied to the 6 studied thin sections. A continuous limit, through the horizontal cross section (Figure 31) and 3 limits through vertical cross section (Figure 32) were identified.

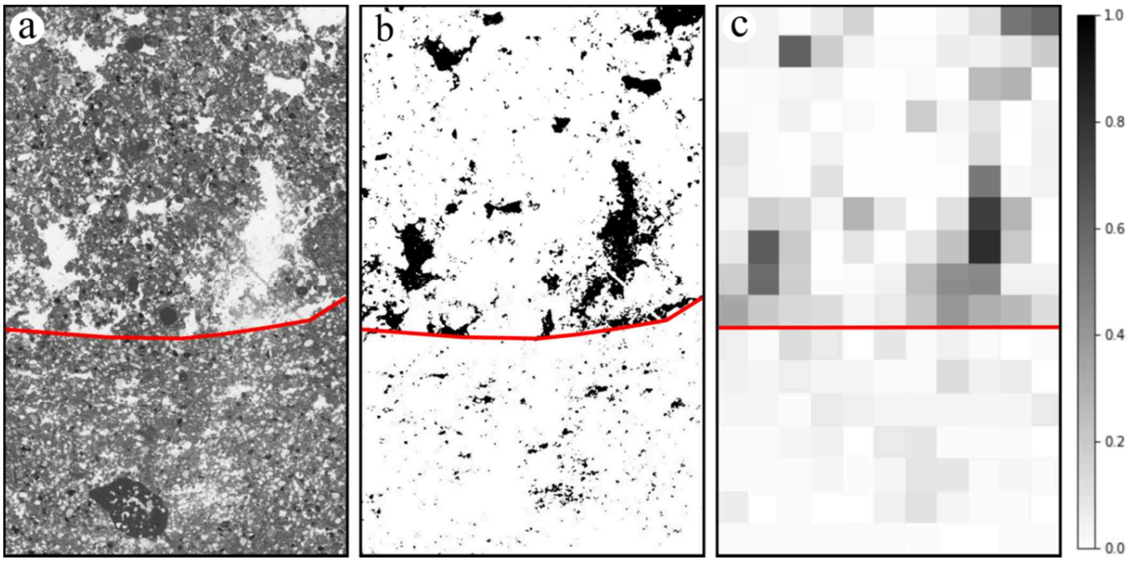


Figure 30. Detail of a rammed earth layer limit, marked with a red line, in grey scale (a), after binarization (b) and in porosity map (c).

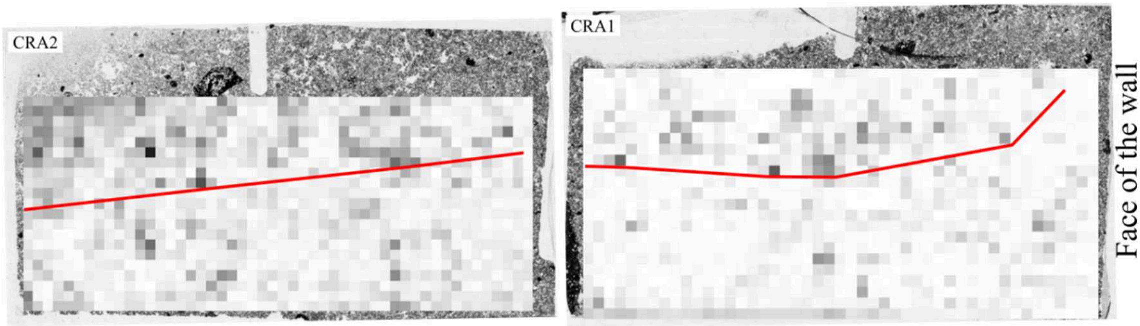


Figure 31. Horizontal section of rammed earth wall after image analysis. A continuous limit (red line) is identified through CRA1 and CRA2 thin section.

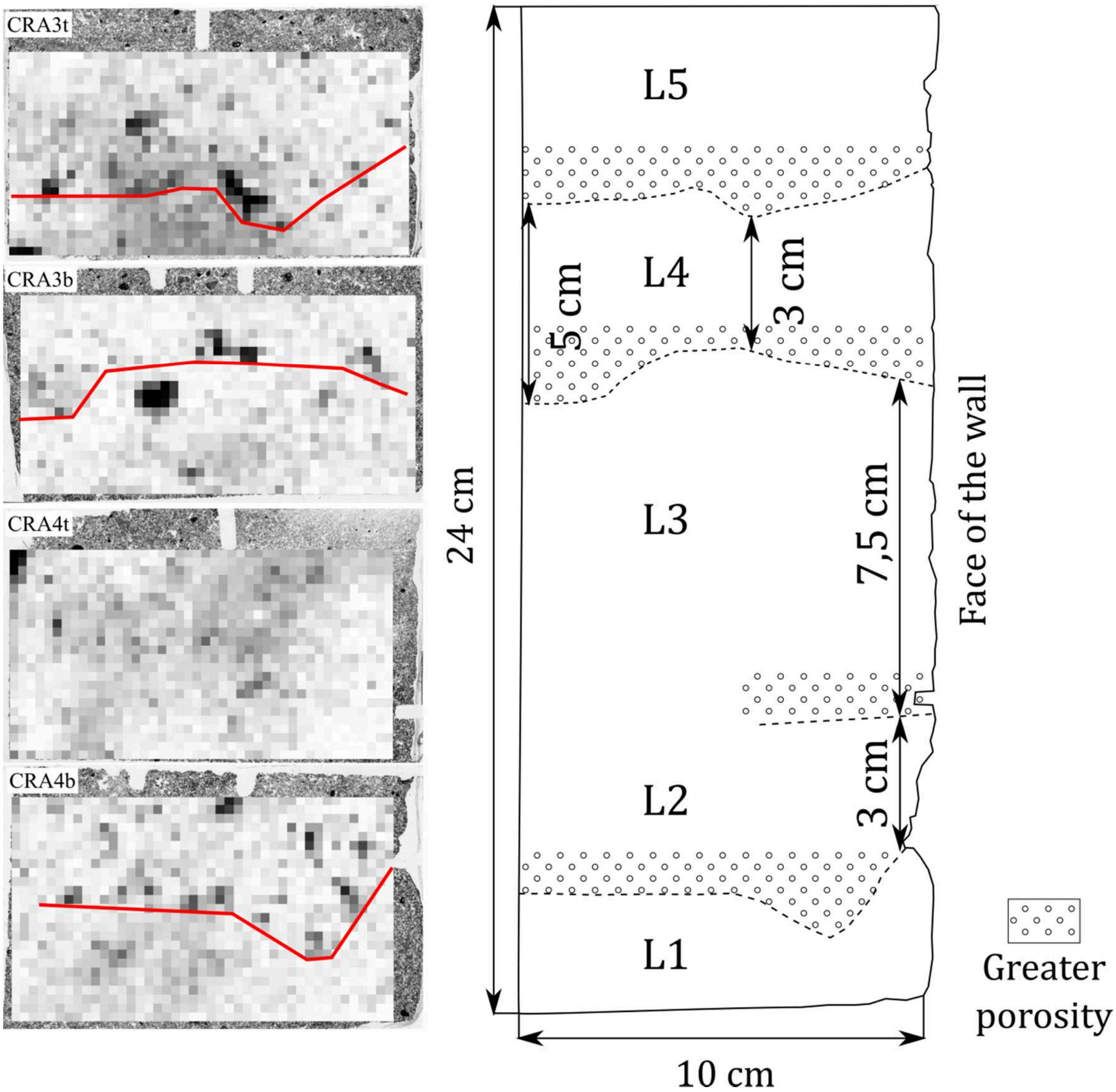


Figure 32. Vertical section of rammed earth wall after image analysis, on left, together with micromorphological analysis results, on right. Three of the four rammed earth layers limits observed by microscope can be detected by image analysis (red lines).

Rammed earth layer limits identified thanks to porosity analysis are in agreement with the limits identified with the naked eye. Nonetheless, a limit observed in CRA4t thin section was not detected by porosity analysis. Actually, the thickness of CRA4t thin section is reduced in its centre (Figure 33) and brightness is therefore high which bias the image processing results. Under these circumstances, it is impossible to analyse the porosity results of CRA4t thin section. This methodology requires thin section with a homogeneous thickness.

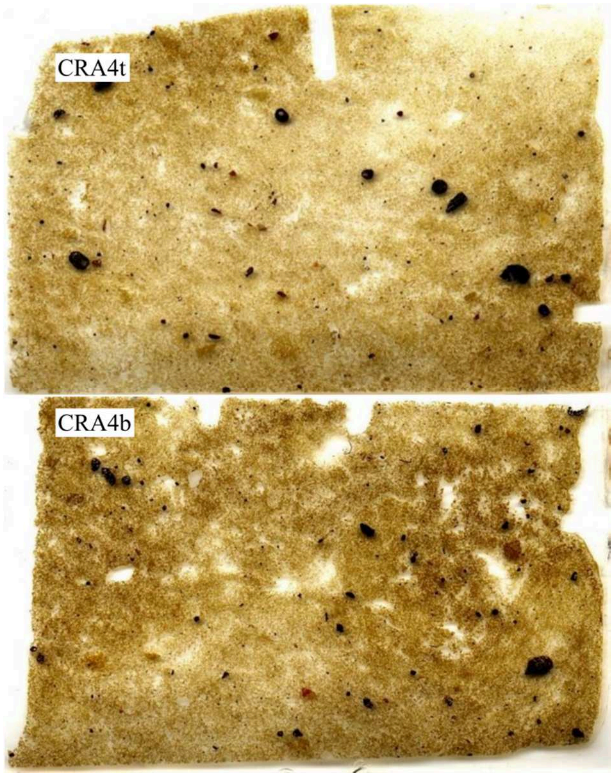


Figure 33. Effect of thin section thickness on brightness

3.4.4.4 Image analysis - Synthesis

An image analysis methodology is proposed to draw the porosity map of thin sections of rammed earth material and able the identification of rammed earth layers limits. Porosity is identified thanks to the addition of PPL and XPL images of thin sections, in order to increase the contrast between voids and quartz minerals. This methodology provides satisfactory results as long as the thickness of thin section is homogeneous. This methodology could be enhanced with the acquisition of a second XPL image with another polarizer position in order to change quartz extinction angle. The combination of one PPL and two XPL with different polarizer orientation might enhance the contrast between voids and quartz minerals.

3.4.5 Rammed earth micromorphological analysis - Synthesis

The micromorphological analysis allowed determining a low mixing degree and a low water content of manufacturing stage. It also permitted describing the effect of the manual rammer during the tamping phase and distinguishing rammed earth layers that were not visible on-site.

The methodology proposed here provides extensive information on the construction process (excavation method, transportation, mixing, water content, compaction effect) employed to build this rammed earth farm, and to make the connection between this process and the type of earth used. By applying this methodology to buildings of different ages and different geographical contexts (soil type, climate, seismicity) it is possible to describe the evolution of the rammed earth processes and their adaptations in specific contexts. Finally, in case of a doubt about the nature of the construction process used for a construction, this method provides clear micromorphological criteria for identification of rammed earth process, applicable to built heritage and archaeological material.

The methodology proposed in this section is promising. Future developments of this work could be: to provide quantitative information in order to support observations, to investigate other rammed earth constructions, with different implementations, from various regions and/or of diverse ages with the aim to experience this methodology.

3.5 Micromorphological analysis of a cob building

3.5.1 Materials and methods

3.5.1.1 Study area

Renovation works performed in a barn, located in the locality of La Poterne in the city of Saint-Gilles (Brittany, France) (Figure 34), gave us the opportunity to collect cob specimens inside a wall built in the early 20th century. The barn is located on a plateau bounded in north-west and south-west by the Mares noirs river, and on the south-east by a dry valley (Figure 35). The bedrock of the plateau is made of Pleistocene loess lying on Brioverian alternations of silts, clays and gravels [285,286] (Figure 35). According to the soil map of Brittany [146], soil of the locality La Poterne derives from shales or silts and are characterized by low argilluviation and variable waterlogging rates (soil map unit 12025, [146]). The topographical position (plateau) and the bedrock composition (loess) allows identifying the soil type of the locality as a Neoluvisol, according to the French soil classification [114], corresponds to Luvic Cambisol in the World Reference Base for Soil Resources [287].

3.5.1.2 Sampling

On the field three construction stages are recognizable in the cob barn (Figure 36). For accessibility reasons, samples were collected in the middle part of the barn. Portions of the wall facing west were cut thanks to a rock chainsaw and brought back to the laboratory (Figure 36 and Figure 37). Smaller undisturbed samples were collected for earth identification purpose and thin section manufacturing (Figure 38). For identification purpose, particle size distribution, according to [288,289] and methylene blue value according to [290] were determined.

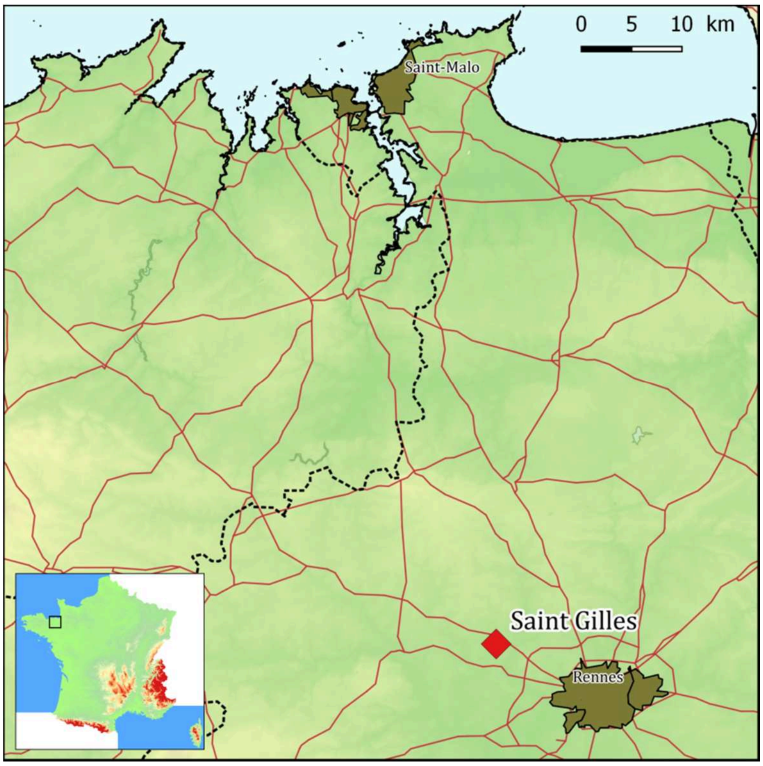


Figure 34. Location map of Saint Gilles (Brittany, France).

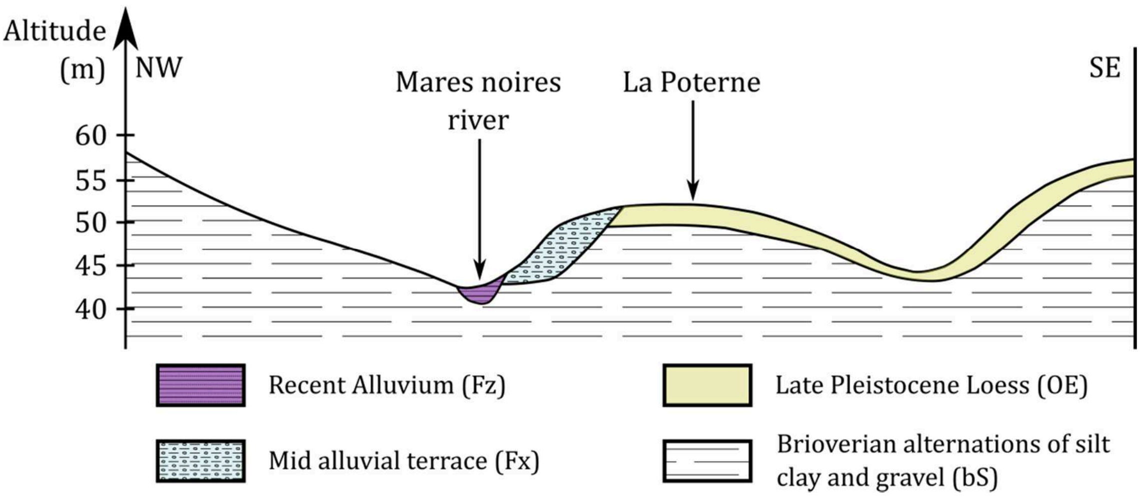


Figure 35. Geological cross section of the locality of "La Poterne", located on the city of Saint Gilles.

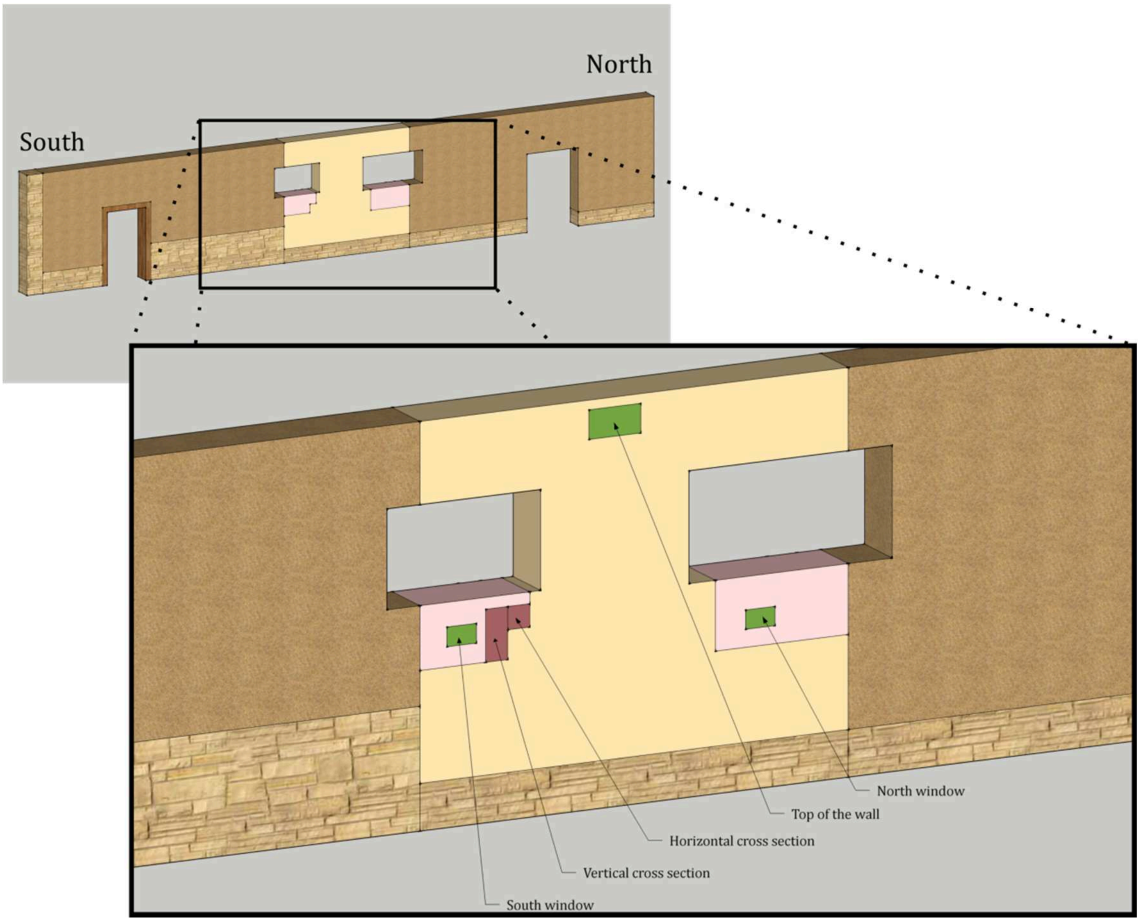


Figure 36. View of the three different construction stages (north, middle and south) identified in the wall, seen from the inside of the building. Sampling concerned the middle stage (in yellow): rose parts were collected, with particular samples for thin sections (red) and material identification (green).

Figure 37. Portions of cob wall cut thanks to a rock chainsaw

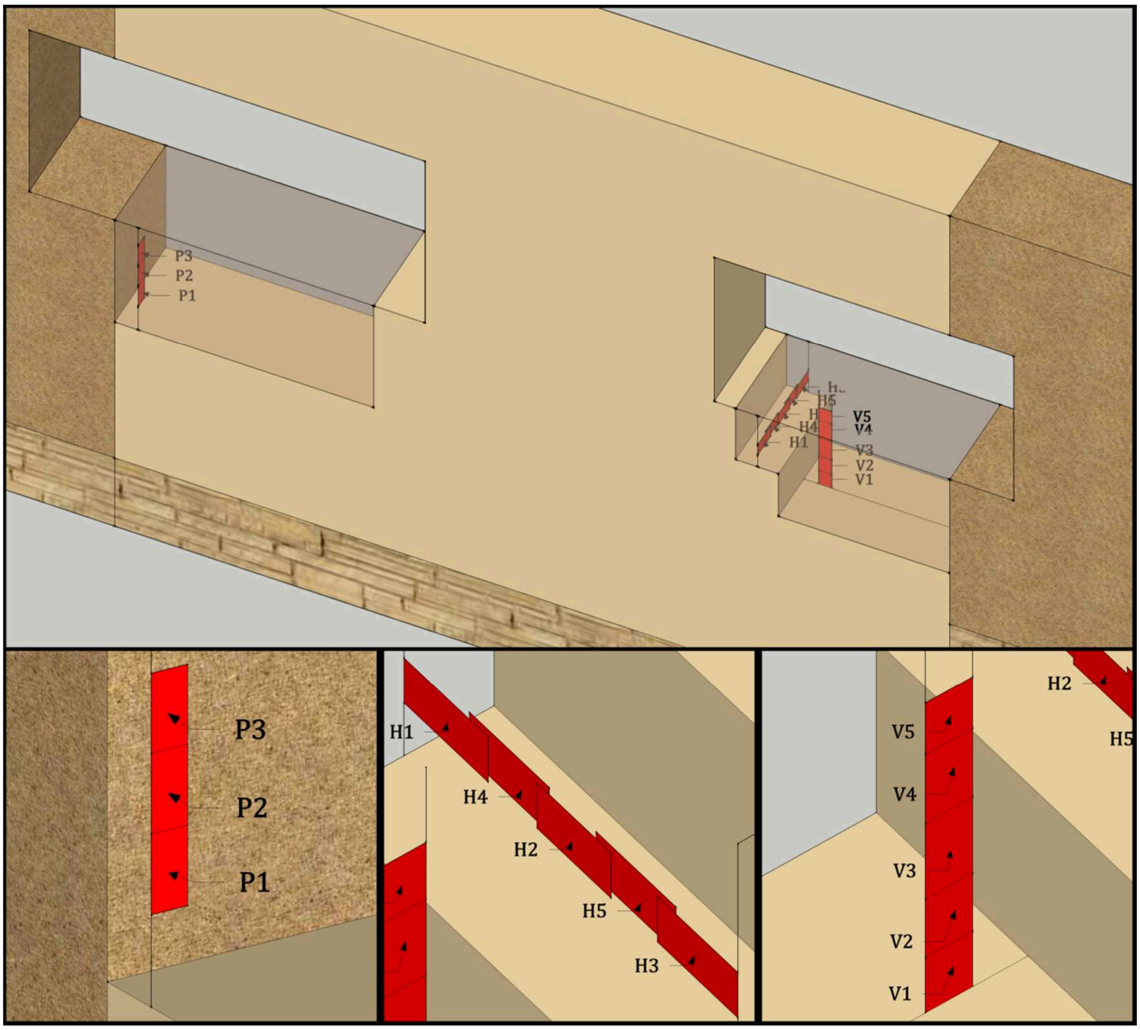


Figure 38. Arrangement of thin sections specimens for plaster cross-section (P), horizontal cross-section (H) and vertical cross-section (V)

Specimens for thin sections production (Figure 38) were cut in laboratory thanks to a table saw. Samples were air dried and then oven dried at 45°C. This temperature minimizes the changes in the mineral structure of the clay and the organic matter of the material. Afterward, according to the protocol proposed by [138], samples were soaked with synthetic resin. After a polymerization of one or two months, a slab of the sample was cut. This slab was temporarily glued to a glass slide. The unattached face of the slab was levelled, ground and glued definitively on another glass slide. The temporary glass slide was removed and the specimen was ground up to 25 µm, reference thickness for micromorphological analysis and for which the transparent observation of the thin section is possible, under Plane Polarized Light (PPL), Crossed Polarized Light (XPL), Oblique Incident Light (OIL) and UltraViolet Fluorescence (UVF). [139]. Finally, a thin glass slide was glued on the second face to protect the thin section.

Thin sections descriptions were performed according to [140] and [139] with the help of [141] and [103] for petrographical description. The abundance of components is evaluated with an abundance charts [140,142]. These references provide a system of analysis and description of soil thin sections. The term groundmass refers to nature, shape and distribution of components; microstructure refers to the spatial arrangement of mineral and organic particles and of voids; fabric refers to the arrangement of the fine fraction (here < 10μm, Table 12) and the preferential orientations of coarse material; inclusions refers to sporadic allochthonous elements; and limits refers to soil discontinuities.

3.5.2 Results

3.5.2.1 Soil identification and macroscale description

Particle size distribution of materials collected in north window, south window and top of the wall (Figure 36) are presented in Figure 39 and textures are shown in Figure 40. Clay, silt, sand, gravel content, methylene blue value and methylene blue activity calculated according to [291], are presented in Table 11.

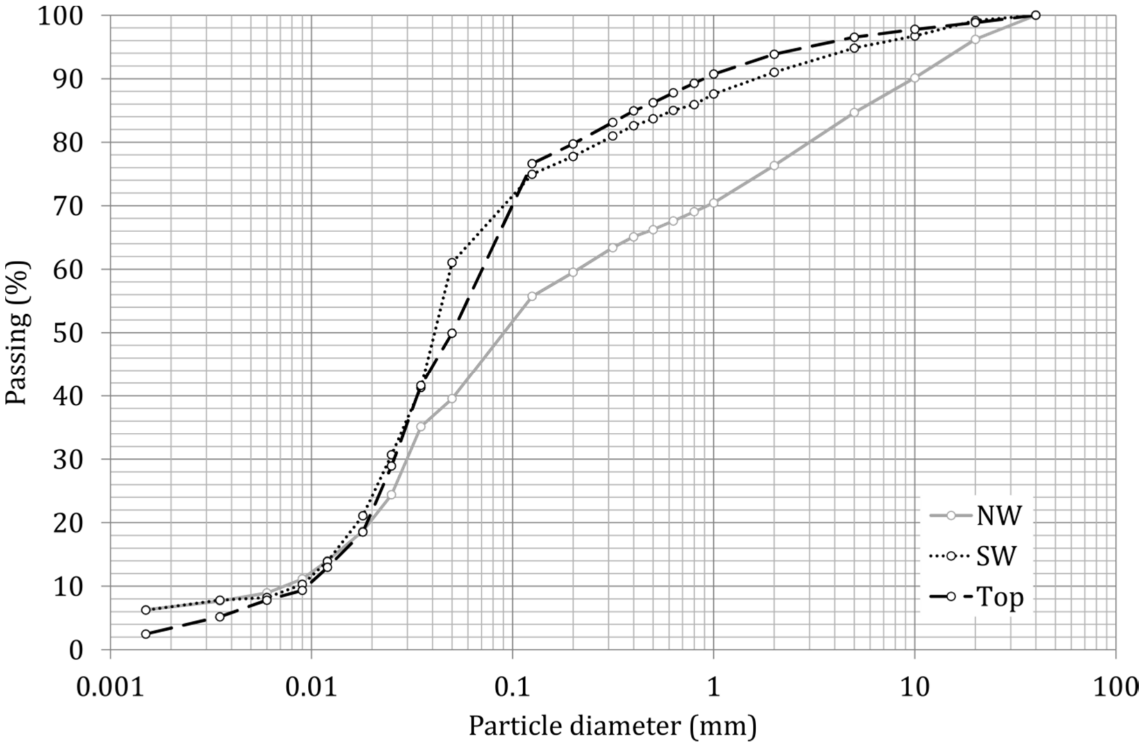


Figure 39. Particle size distribution of material collected in north window (NW), south window (SW) and in top of the wall (Top)

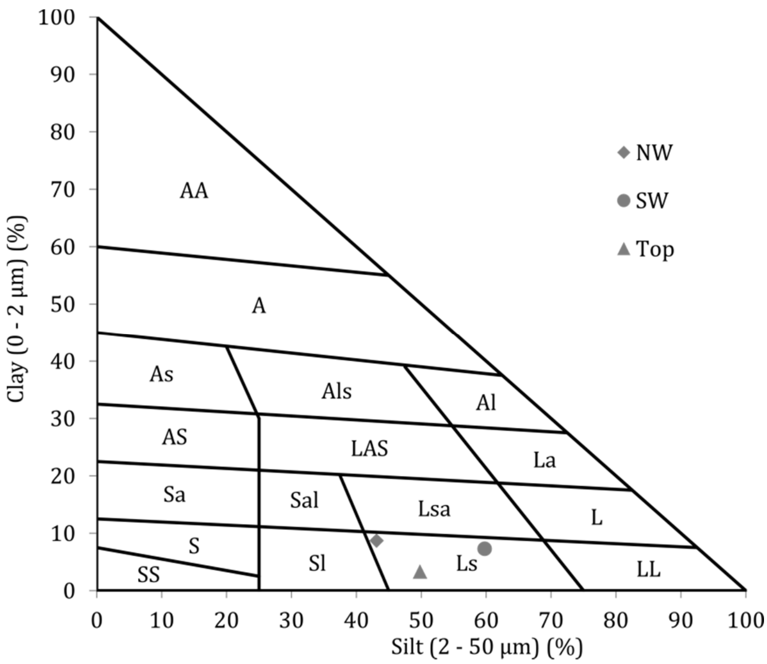


Figure 40. Texture of material collected in north window (NW), south window (SW) and top of the wall (Top) represented in the GEPPA triangle (A = clay, L = silt and S = sand).

Table 11. Identification of material collected in north window (NW), south window (SW) and in top of the wall (Top)

Material	*Clay (0 - 2 µm) (%)*	*Silt (2 - 50 µm) (%)*	*Sand (50 µm - 2 mm) (%)*	*Gravel (> 2 mm) (%)*	*Methylen Blue Value (g/100g)*	*Methylen Blue Activity*
NW	7	33	37	24	0.91	14
SW	7	54	30	9	0.78	12
Top	3	47	44	6	0.69	22

The cob implementation technique employed to build the middle part of the cob barn (Figure 36) is not clearly visible on-site. Wall specimens were water-sprayed in order to better analyse the cob macroscopic wall organisation. This revealed horizontally organised fibre layers (Figure 41), delineating clods of earth (Figure 42). Nonetheless, fibre layers are more or less obvious and are sometimes discontinuous.

Figure 41. Detail of a fibre layer (picture taken from above).

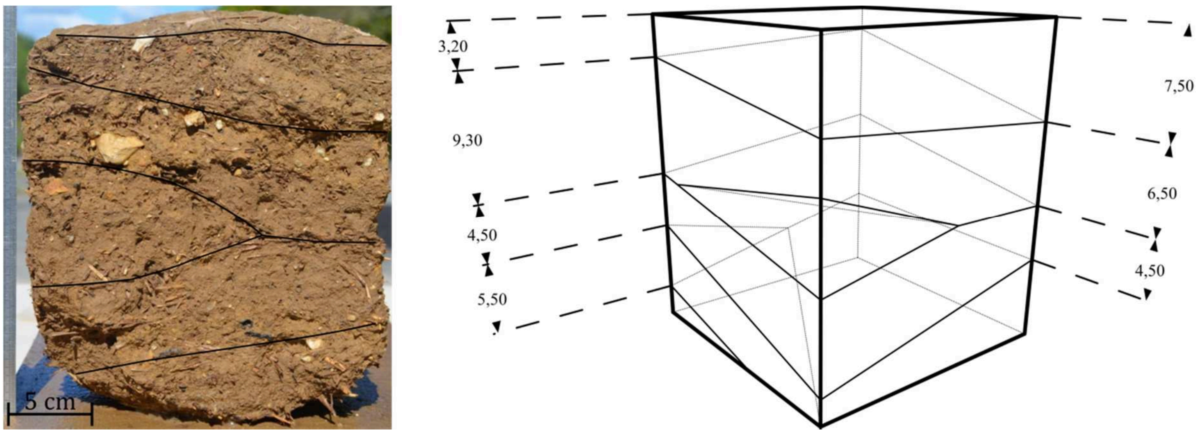


Figure 42. Cob clods limits of a wall portion underlined on a picture (on left) and depicted on a 3-dimension schematic diagram (on right, dimensions in cm).

Pictures of thin sections were used to draw a horizontal and a vertical schematic cross section (Figure 43). The horizontal cross section is perpendicular to the faces of the wall, whereas the vertical cross section is parallel to the faces of the wall. Fibres are visible throughout cross-sections, but they are more specifically concentrated along sub-horizontal planes (Figure 43). Soil aggregates are horizontally flattened and parallel to fibre planes (Figure 43). Vertically oriented voids are clearly visible throughout the horizontal cross section but are less visible in vertical cross-section (Figure 43).

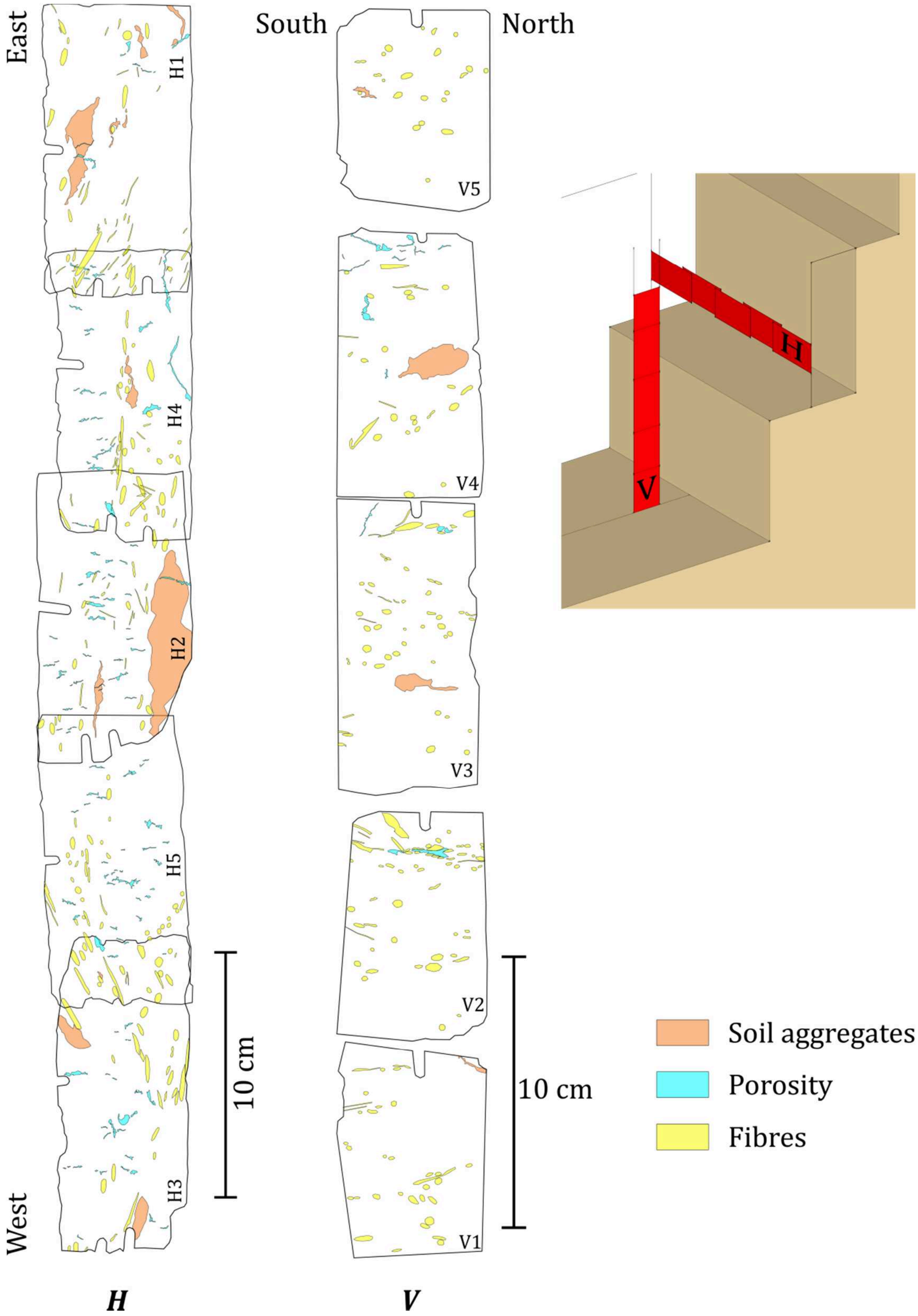


Figure 43. Horizontal (H) and Vertical (V) cross section highlighting thin sections macrostructure.

3.5.2.2 Micromorphological description

A detailed micromorphological description is presented in Table 12. Microstructure of cob material is apedal, with a dominant vughy microstructure, and a minor vesicular microstructure. In vughy microstructure, voids are dominated by round vughs with concave and convex walls, randomly oriented or subhorizontally elongated (Figure 44). Vesicle voids are visible in vesicular microstructure (Figure 44). Vertical planar voids partially accommodated with a pointed edge (Figure 44) are visible all across thin sections, more especially in horizontal cross-section.

Groundmass has a $c/f_{10\mu m}$ ratio of 7/3 with a porphyric distribution pattern. Coarse material is made of (1) mineral grains: dominated by angular quartz silts and sands, rare subangular silt micas and rare subangular silt feldspar; (2) rock fragments: rare subrounded quartzite gravels and rare subrounded sandstone-schists gravels; (3) organic components: few well preserved pluricentimetres straw stem residues (Figure 45a) and rare inframillimetres plant organ fragments; (4) rare soil aggregates containing subrounded quartzite gravels, (5) very rare bones and (6) very rare ceramics. Fine material is made of yellowish brown speckled clay.

Textural, impregnative and amorphous pedofeatures are observed in the earth material. Textural pedofeatures are (1) occasional non-laminated coatings of voids (Figure 45b) or stems (Figure 45c), most of the time in normal position with regard to wall gravity, with a material dominated by 5–100 µm angular quartz, sometimes covered with a layer of fine material and sometimes associated with groundmass fragments (Figure 45b) ; (2) occasional non-laminated impure clay intercalations inside groundmass (Figure 45d); (3) occasional plurimillimetres clay depleted zone inside groundmass (Figure 45e). Impregnative pedofeatures are (1) occasional moderate to strong Fe-Mn coatings and hypo-coatings of voids (Figure 45f); (2) occasional moderate to strong Fe-Mn internal and external hypo-coatings of plant fragments (Figure 45g); (3) occasional moderate to strong Fe-Mn impregnations of groundmass (Figure 45h). Amorphous pedofeatures are rare plurimillimetres typic nodules with sharp or gradual boundaries.

From thin section analysis, two main fabrics can be distinguished: Fabric 1, the most represented, with a randomly distributed sand fraction inside a silty-clayey fine material, and Fabric 2, locally sand particles, stems, intercalations and clay depleted area are sub-horizontally organized (Figure 46a, a and c) and sometimes this organisation is oblique (Figure 46d). These limits are located in or near stem concentrations areas (Figure 43) and are not continuous all along thin sections. These limits are also associated with broken stem residues (Figure 46a, c and d) and with sheared (Figure 46e and f) deformed (Figure 46g) or rounded (Figure 46h) soil aggregates.

Table 12. Micromorphological description, after [139,140]

Microstructure			*Total porosity by volume (%)*	10 - 20			
			Aggregates type	Apedal			
			Microstructure type	Vughy			Vesicular
			Total proportion (%)	50-70			< 5
			Void type	Vughs	Planar	Vughs	Vesicles
			Size of voids (mm)	0.5 - 3	1 - 20	0.5 - 2	0.5 - 1
			Relative proportion (%)	30 - 50	30 - 50	15 - 30	15 - 30
			Orientation pattern	Random	Vertical	Horizontal	Random
Mineral and/or organic components	*General*		*Coarse/fine limit (µm)*	10			
			c/f ratio	7/3			
			Sorting	Poorly sorted			
			Related distribution	Porphyric			
	Coarse components		*Proportion mineral (%)*	>70			
			Proportion organic (%)	5 - 15			
		Mineral grains	*Main types*	Quartz	Mica	Feldspar	
			Size	20 µm - 2 mm	20 µm - 100 µm	10 µm - 30µm	
			Sorting	Poorly sorted	Well sorted	-	
			Shape	Angular	Subangular	Subangular	
			Total proportion (%)	> 70	5 - 15	< 5	
			Degree of alteration	Weak	Moderatly weak	Moderatly weak	
		Rock fragments	*Main types*	Quartzite	Sandstone schists		
			Size (mm)	3 - 30	1 - 25		
			Sorting	Moderately sorted	Moderately sorted		
			Shape	Subrounded	Subrounded		
			Total proportion (%)	< 5	< 5		
			Degree of alteration	Moderatly weak	Moderatly weak		
		Organic components	*Main types*	Organ residues (stem)	Plant residue		
			Size	1-50 mm	0.5-1 mm		
			Shape	Acicular	-		
			Total proportion (%)	5 - 15	< 5		
			Communition	Whole organs	Organ fragments		
			Preservation	Good	Moderate		
		Other	*Main types*	Soil agregates	Bones	Ceramic	
			Total proportion (%)	< 5	< 5	< 5	
	Fine material		*Proportion mineral*	> 70%			
			Proportion organic	< 5%			
			Main colour	Yellowish brown			
			b-fabric	Speckled			
			Limpidity	Speckled			
Pedofeatures	*Textural pedofeatures*		*Type*	Coating	Intercalations	Clay depletion	
			Size	0.5 - 5 mm	2 - 20 µm	1 - 5 mm	
			Lamination	Non-laminated	Non-laminated	Non-laminated	
			Texture	Silt and clay	Impure clay	Silt	
			Colour	Yellowish brown	Yellowish brown	Grey	
			Related to	Stem and voids	Groundmass	Groundmass	
			Abundance	Occasionnal	Occasionnal	Occasionnal	
	Impregnative pedofeatures		*Type*	Hypo-coating	Int/ext hypo-coatings	Impregnation	
			Nature	Fe-Mn	Fe-Mn	Fe-Mn	
			Related to	Voids	Plant fragments	Groundmass	
			Size	0.5 - 10 mm	100 µm - 10 mm	100 µm - 5 mm	
			Degree of impregantion	Moderate - Strong	Moderate - Strong	Moderate - Strong	
			Oblique incident light colour	Red	Red	Red	
			Abundance	Occasionnal	Occasionnal	Occasionnal	
	Amorphous pedofeatures		*Type*	Nodules			
			Abundance	Rare	Rare		
			Size	100 µm - 5 mm	100 µm - 5 mm		
			Nature	Typic	Typic		
			Boundary	Sharp	Gradual		
			Relative proportion (%)	30 - 50	30 - 50		

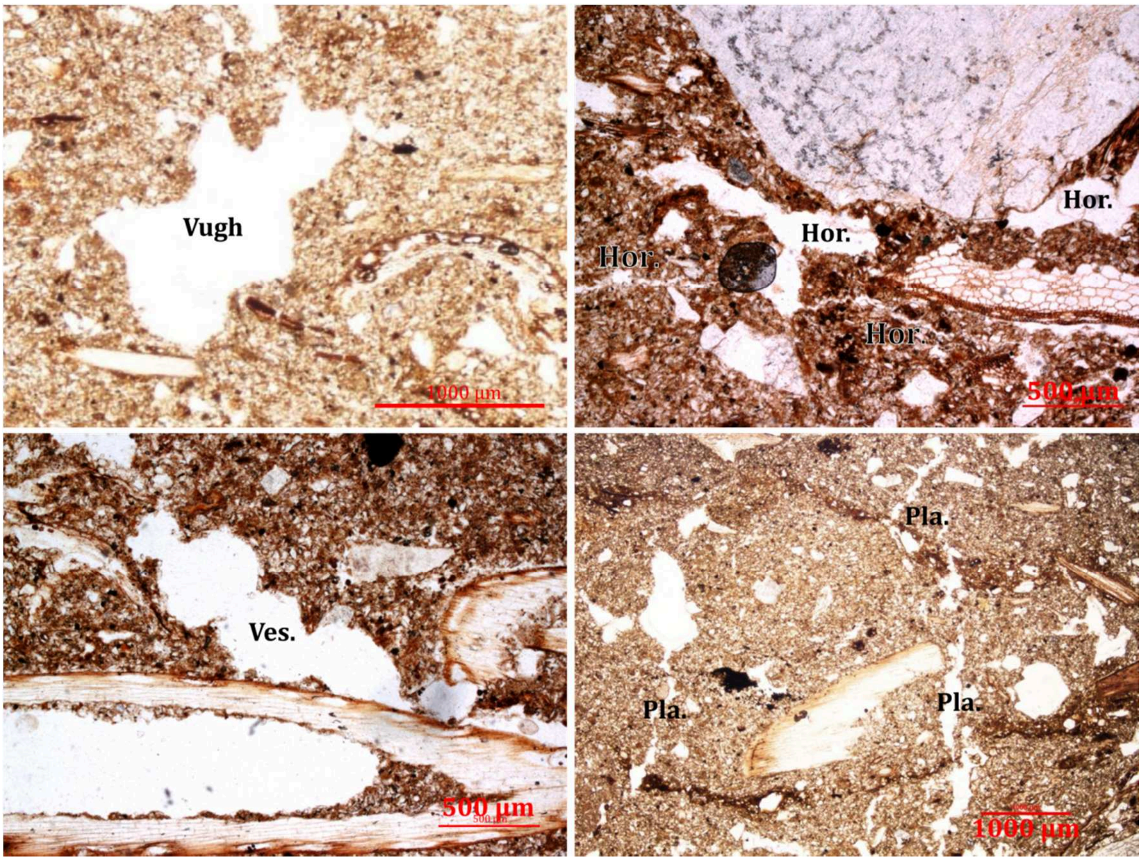


Figure 44. Microscope pictures of voids type: Vugh = random vughs; Hor. = horizontal vughs; Ves. = vesicles; Pla. = vertical planar voids.

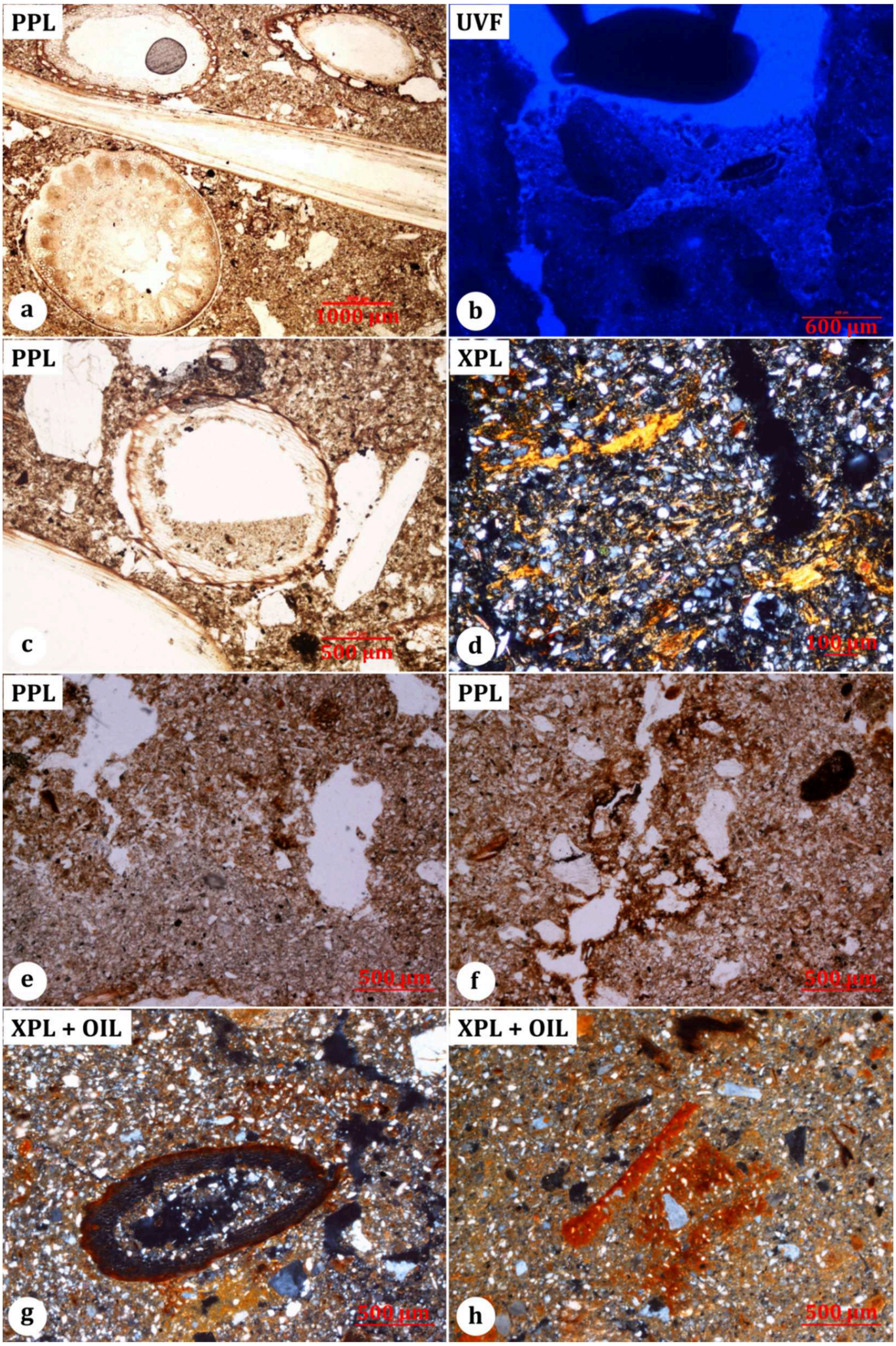


Figure 45. Microscope picture of a: stem residues; b: void coating; c: silty coating in the section of a stem; d: intercalations; e: clay depletion at the lower part of the photo; f: voids coating and hypo-coatings; g: stem internal/external hypo-coatings; h: Fe/Mn groundmass impregnations.

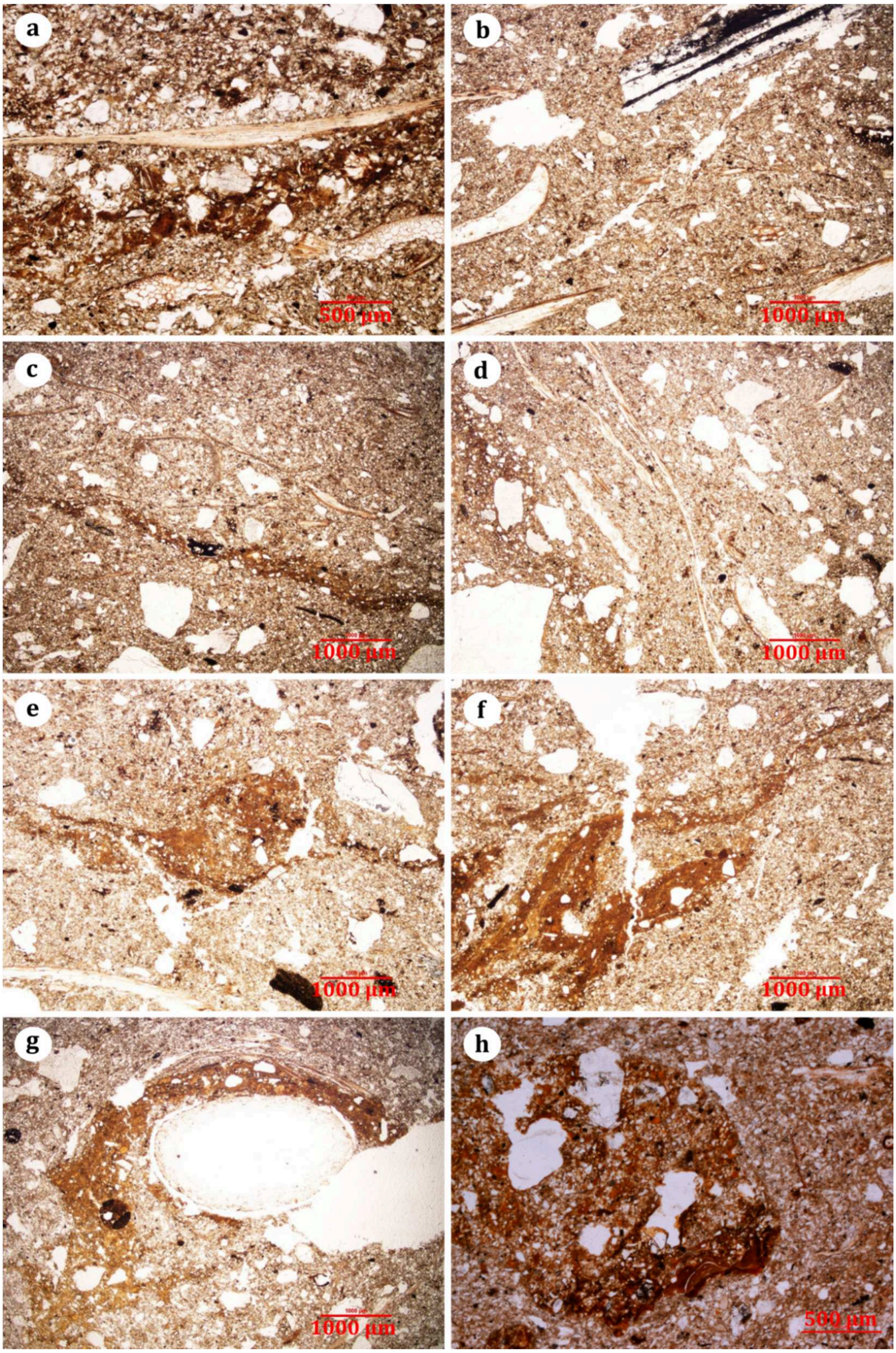


Figure 46. Fabric pedofeatures: subhorizontal limits (a, b and c) and oblique limit (d) underlined by sand alignments stems and voids parallel to the limits, deformed soil aggregates (e, f and g) and round aggregate (h). All pictures are taken in PPL.

3.5.3 Discussion

3.5.3.1 Excavation

Angular quartz, micas, feldspar and sandstone schists most likely come from the alteration of the Brioverian formation, whereas subrounded quartzite gravels, associated with soil aggregates, most likely derive from an old alluvial deposit. It is to be noted that, even located on eolian deposits (Figure 35), no eolian quartz was observed in thin sections.

Anthropogenic remains (bones, ceramics) are very few in the earth material, indicating a non-superficial material origin and that the material does not come from the reuse of a past cob wall. Groundmass has few plant residues such as fine roots or herbaceous fragment and exhibit low finely organic components with a high degree of comminution. These observations confirm the non-superficial material source.

Material collected in the north window has a higher gravel content (Figure 39 and Table 11) and material collected in the top of the wall has a lower clay content than the other ones (Figure 40 and Table 11). These differences are deemed compatible with horizontal and vertical natural variations inside a unique soil horizon. It is then reasonable to consider that the excavation of the earth may have concerned a unique site.

3.5.3.2 Fibre addition

Stems observed in thin sections correspond to straw fibres observed by naked eye. Their vegetal cells are clearly visible and have a high birefringence (Figure 45a), highlighting a slight ageing. Fibre abundance and their organization in layers (Figure 41, Figure 42 and Figure 43) pointing out an intentional fibre addition by past builders.

3.5.3.3 Clod limits

Limits of clods are visible at macroscale (Figure 42) and are underlined by fibre layers (Figure 41). These limits are still visible by naked eye observation of thin sections (Figure 43) but are less obvious under microscope observation. At microscale, clods limits are better depicted as a transition zone, underlined by subhorizontal fibre concentration, associated with subhorizontal vughs and quartz alignments (Figure 46a, b and c) and sometimes with vesicles (Figure 44).

3.5.3.4 Mixing

Several pedofeatures, like (1) Sub-horizontal voids located beneath fibre or quartzite (Figure 44), (2) straw fibres filled with earth (Figure 45c), (3) in-situ fragmentation of straw fibres (Figure 46c), (4) sheared and horizontally flattened soil aggregates (Figure 46e and f), (5) straw fibres forced inside soil aggregates (Figure 46g) and (6) rounded soil aggregate (Figure 46h), highlight a kneading action of earth material at plastic state with straw fibre addition. This is in line with traditional cob mixture preparation, prior to implementation, which usually involved the treading, by men or animal, of earth at plastic state together with fibres (section 3.3.2.5). Nonetheless, since these pedofeatures are predominantly in a normal position with regard to wall gravity, they could also be attributed to a compaction of clods inside the wall during implementation or drying phase. As clods are implemented sub-horizontally, it is not possible to make the distinction between compaction pedofeatures linked to treading of cob mixture and, if it has been the case, those linked to clods compaction inside the wall.

Quartz particles are not evenly distributed in the groundmass and straw fibres are mainly located at clods limits. The blending action of cob mixing is very limited. In this case, cob mixing is dominated by kneading, which forces straw fibres inside the surface of earth material and allows water ingress in order to reach a homogeneous consistency of cob mixture. The construction technique employed here can be identified as a local constructive technique of Brittany called "*caillibotis*", case (b) section 3.3.3.1. It is then possible to propose a description of the technique employed for the cob wall construction. A layer of fibre was spread on the ground, then a layer of earth, and another layer of fibre. The whole was wetted and trod by foot, so that fibres penetrate faces of cob mixture layer, and cut into squares. These squares, or clods, were pilled horizontally inside the wall.

3.5.3.5 Clay depletion and intercalation

Clay depletions are visible in some areas inside groundmass (Figure 45e), in the material inside some fibres (Figure 45c) or in material inside some voids (Figure 45b). During kneading and/or clods implementation, compaction of the material at plastic state lead to water flow of excess water. Water flow preferentially circulated inside high porosity areas, voids and fibres, discontinuities and leached clays and sometimes fine silts, depending on the speed flow.

3.5.3.6 Impregnations

Fe and Mn oxides occur when the soil is saturated with stagnant oxygen-depleted water during at least several days, with the presence of sufficient organic matter and microorganisms and with a temperature above 5°C [292]. Straw fibres added in cob mixture are affected by Fe/Mn impregnations (Figure 45g). Implementation of clods of cob was usually made right after the cob mixture treading or, at most, one day after kneading (section 3.3.3.2). According to literature this time period seems not sufficient to generate impregnative pedofeatures. Impregnations observed in thin sections had developed at the beginning of the drying of the wall, at least for those affecting straw fibres.

Broken impregnations, clay depleted deposits in void included in an impregnation and impregnated plant residue perpendicular to the general orientation of the earth material observed in thin sections prove that a part of the impregnations took place before wall drying. These impregnations could be inherited from the initial soil, could be related to an intentional rotting of soil, prior to construction, in order to reduce organic matter content, or, if organic matter was added, for stabilisation purpose (section 3.3.2.4). No intentional fine organic matter addition in the groundmass for stabilisation purpose was highlighted in thin section observation. The little vegetal residues content of the groundmass and the Fe/Mn impregnations of the groundmass could be attributed to an intentional rooting of the soil prior to construction or could be inherited from the initial soil.

3.5.3.7 Shrinkage

Vertical planar voids intersect all pedofeatures types observed in thin section and are visible across all thin sections, more specifically across horizontal cross-section (Figure 43). These vertical voids are interpreted as shrinkage cracks. It is to be noted that shrinkage is more pronounced in the direction perpendicular to the face of the wall than in the direction parallel to the face of the wall.

3.5.4 Cob micromorphological analysis - Synthesis

Micromorphological analysis of this cob material highlighted: (1) a clear kneading action at plastic state attributed to the cob mixture trampling, (2) a limited or no blending action, (3) water flow responsible for clay depleted and intercalation areas, attributed to cob mixture trampling and possibly also to compaction of cob clods during implementation in the wall, (4) impregnations of Fe and Mn oxides attested during wall drying and hypothetically during an intentional rooting of material prior to mixing. Besides micromorphological analyse, macroscale observations were essential in order to understand the general clods organisation. For cob wall study, microscale and macroscale descriptions are both required. Combining these two observation scales, it was possible to identify "*caillibotis*" as the construction technique employed for this building.

3.6 Synthesis of chapter 3

Micromorphological analysis of features deriving from construction process provides information on the mixing degree, the water content of manufacturing stage, the deformations associated with kneading or compaction action and the organisation of clods/layers. All these elements permit to propose an accurate description of the construction technique employed by past builders. For the rammed earth and the cob building studied here, we succeeded rediscovering the construction process employed by past craftsmen.

Table 13 draw a comparison of micromorphological features related to the rammed earth farm and the cob barn at different process stages. Rammed earth vernacular construction techniques show little variations and, to a certain extent, rammed earth can be regarded as a standardized process. Features highlighted for the rammed earth farm in Table 13 can thus be used as a basis to assess micromorphological characteristics of rammed earth. This is not the case for the cob barn. Indeed, cob process shows large variations (section 3.3.5) and the features proposed in Table 13 for the cob farm only concern the "*caillibotis*" technique.

Table 13. Micromorphological features allowing distinguishing the rammed earth farm of Cras-sur-Reyssouze and the cob barn of Saint-Gilles, at different process stages (W_m = water content of manufacturing stage).

Process stage	Rammed Earth	Cob
W_m	Porosities with rough and irregular walls indicates a solid state (section 3.4.2)	Vesicles, clay depletion and intercalations indicates a plastic state (section 3.5.3.4)
Mixing		Plastic deformations of soil aggregates, straw fibres filled with earth, clay depletion and intercalations indicates a kneading action (section 3.5.3.4)
Limits	Layers are underlined by obvious and continuous limits outlined by sand alignments, subhorizontally elongated voids and a contrast between an above high and a below low porosity (section 3.4.3)	Clods limits are underlined by fibre layers by naked eye and, at microscale, by a transition zone associated with subhorizontal fibres concentrations, flattened voids and sand alignments (section 3.5.3.3)
Compaction	Inside rammed earth layers, ramming process generates overlapping discontinuous limits, horizontally oriented associated with a shortening, oblique shear lines, sometimes combined together to create corner shape figures (section 3.4.3)	
Drying		Drying is associated with Fe and Mn impregnations, affecting fibres added in cob mixture, and with vertical shrinkage cracks, more pronounced in the direction perpendicular than parallel to the face of the wall (section 3.5.3.6 and 3.5.3.7)

If micromorphology applied to earth buildings provides detailed information on the construction process, it necessitates collecting samples in heritage buildings and it involves a long samples preparation and investigation. This method is time-consuming and it is not possible to study large heritage corpus. Studied buildings should, therefore, be carefully selected. This method could complement heritage study, by selecting, for example, some typical buildings for each architectural typology and original case-studies. It can also be used prior to heritage restoration works, in order to identify and reproduce the construction technique employed by past builders.

Some improvements can be proposed for this methodology. This more specifically concerns the determination of water content of manufacturing stage, which has a great impact on kneading/compacting action. Only the material state, i.e. solid, plastic or liquid, can be determined presently. The identification of a physical parameter, correlated with water content, should enable the determination of the water content of manufacturing stage. Another outlook for future could be the utilisation of image analysis to go from a phenomenological approach to a physical approach. However, pedofeatures are complex and multiscale objects and their study requires a high expertise. The development of such image analysis tools would necessitate a significant effort, but could lead to study large collections of thin sections and refined material characteristics and construction processes.

Chapter 4 Earth construction in modern sustainable building

4.1 The challenge of modern earth construction

4.1.1 Introduction

Modern earth construction sector faces many issues. In Western countries, major issues identified in the literature [1,4,19,27,57,253,293] are a high cost of construction, a lack of standard, a lack of knowledge, ignorance of consumers, contractors and professional of the building industry, inappropriate national regulations and a lack of formation. The review of modern earth construction issues is a wide and complex subject and would require an extensive socio-economic analysis, which is outside the scope of this thesis.

Anyhow, earth construction issues are determined considering mainly rammed earth, compressed earth blocks and adobe techniques. Cob is rarely considered in the modern building while this rich process can shed a new light on modern earth construction. Section 4.1, therefore, focuses on cob as a sustainable construction material for modern building but aims at feeding the discussion on modern earth construction. The past and present innovation of cob (section 4.1.2), interaction with society (section 4.1.3) and the future of cob (section 4.1.4) are discussed in this section.

4.1.2 Cob, a process in constant innovation

Cob is a slow and labour intensive process. Cob masons have experimented alternative construction techniques in order to ease the construction process and to save time. Generation after generation, cob masons better understood the behaviour of the material and enhanced their techniques. This innovation process is highlighted by the reduction of wall thicknesses, as illustrated in section 3.3.3.2. The use of animal power for mixing, the development of specific cob tools, the "quick process" and the use of shuttering are other examples of past innovations (section 3.3.3.1).

More recent cob innovations involved: (1) use of damp proof courses, (2) prefabrication, (3) mechanization and (4) new mixing and implementation techniques.

Plinths of cob heritage walls are made of stones and earth or lime mortar [14,27,35,65,77,115,116,152,156,200,210,244,252,255,261] that may drive capillary rise. Consequently, cob walls are exposed to humidification by capillary rise. If excess water is not evacuated from the wall, the water content of the cob wall can rise and lead to poor thermal comfort and/or structural damages [13,22,35,152,251]. In Germany, layers of compacted clay underneath foundations of cob heritage buildings dating back to 17th up to 19th century were interpreted as poor damp proof courses [12]. The first mention of efficient damp proof courses made of bitumen cardboard concerned cob houses in the beginning of the 20th century [12,155]. The use of cement concrete in lieu of stone masonry for the plinth during the 20th century also participated to the protection of the cob walls from capillary rises [15,116,263].

Prefabrication of cob elements is a way to reduce the wall fabrication time [19]. Plastic elements of earth cut or modelled (case b and c, section 3.3.3.1), i.e. *Gazon*, *Massone* or *Banco* techniques, can be regarded as prefabrication techniques. The regular shape of earth elements eased their placing on the wall and their dry-plastic state accelerated the drying of the wall. Joce [154], in 1919, proposed a cob prefabrication process which however seems that it had never been employed. Another prefabrication process has been developed and employed by Jean Guillorel in Brittany in the 1980's [161,201,222]. Cob mixture was poured in a mould that contained two hooks attached to three wooden pieces disposed on the bottom of the mould. Hooks were employed to handle cob elements. Cob elements were unmoulded 24 h after pouring and left to dry for 1 month. The height of the prefabricated cob elements was 50 cm, the thickness was 40-50 cm and length was 50-70 cm. Elements were assembled in the wall thanks to a crane and jointed with an earth stabilized mortar [161,201,222].

Mechanization of the mixing of cob reduced the number of workers required, the work painfulness and should improve the mixing action. The first mention of mechanization of the cob mixing was made by Clough Williams-Ellis in 1920 [244]. The author stated that a power-driven "pan-mill" has been tried with success. Since then, attempts have been made to mix cob, using machines such as concrete mixer [22,37,47,120,252], mortar mixer [22], vertical shaft mixer [16,161,201], rotavator [22] and clay brick mixer [18]. The kneading action of most of these machines was too little to force the straw and clay into contact. Thus, they required a higher water content of manufacturing stage, which increased the drying time. Those machines are considered as inappropriate for cob mixing [22,37,47,120,252]. Another mechanized technique developed in England consists in treading the cob mixture thanks to the wheels of a digger and in stirring it thanks to the digger bucket [22,34,37]. The mixing action of the digger is judged satisfactory but, as for other mechanized techniques, it required higher water content of manufacturing stage. It was then necessary to let the cob mixture drying for a while before implementation [22,34].

New mixing and implementation methods were developed in the USA during the 1980's and 1990's [15,36,47,263]. These methods introduced the use of tarp to stir the cob mixture and the implementation of cob by hand, using a thumb, a stone or a stick. Reedcob is a new cob implementation technique developed in Portugal that consists in employing giant reed cane as bond beams [294].

Joce [154] did a clear distinction between an old-fashioned cob method and a modern one involving mechanization and prefabrication. However, innovation concerned the past period as it concerns the modern one. For example, animal treading can be regarded as a mechanized process and moulded clods of cob or adobe technique can be regarded as prefabrication processes. In fact, it is quite difficult to draw a line of demarcation between an old cob process and a modern one. The modern cob is in the continuation of the vernacular cob.

4.1.3 Cob and society

Social, economic and technical evolutions of societies had a great impact on the evolution of the cob process [59,64,174]. Until early 20th century in Europe, masons moved by foot or by bicycle and building materials were transported by animal-drawn tumbrel [177,210,249]. Consequently, masons had to use locally available materials and had a range of action restricted to a few kilometres [93,152,175,177,210,259]. This isolation was more dramatic in marshlands [156,211,214]. Cob construction process know-how was orally transmitted generation after generation [16,22,27,117,226,234,250] and the limited transportation means did not foster the exchange of know-how between cob masons. This generated local practices and habits for construction [59,152,175,177]. This is illustrated by the variety of the names given to cob mixture in Brittany that were different from a town to another [174,175]. In Europe at the end of 19th century, the railway brought stones and new construction materials (brick and cement) that entered in competition with cob [59,93,152,164,197,211,244,252].

Cob site work required an important workforce [201]. Usually, a skilled cob mason, eventually accompanied by 1 or 2 employees or apprentice, conducted site operations [116,152,210,249]. The workforce was supplemented by the owner helped by his family and his neighbours [156,193,200,210]. Sometimes cob houses were self-build by the owner [76,116,150,152,161,234]. In all cases, mutual aid brought by the neighbours' workforce was essential to face cob site work [197,201,234]. Mutual aid relied on the reciprocity of favours. In Brittany, another way to motivate neighbours to give a hand on site involved free cider, traditional music and songs to make them dancing and singing while treading cob [158,174]. Rural migration depleted available workforce and know-how, and commodification broke rural solidarity [77,163,197,226,234,250]. Without mutual aid system, labour charge became unaffordable for a part of the rural population [31,201]. Mechanization of the process was an answer to this issue [31].

In Europe, before 1900, because cob houses were cheap to build, it was the unique affordable construction for a part of the population [31,210]. For them, it was therefore not a choice but a constraint that highlighted their social class [212,295]. Therefore, for a large part of the population, cob was synonymous with poverty, archaism, unhealthiness and low strength [22,59,116,125,150,156,163,164,201,209,264]. This is why where stones were available it was preferred to earth as a building material [77,93,200,206,250]. Earth was considered as a default material choice [210]. However, some authors noted that in late 19th and early 20th century, high-status buildings were built in cob (manors, schools, town halls, churches) proving that cob is not only a building material for the poor [34,64,65,76,125,152,199,201,206,296]. Nevertheless, with the introduction of industrial building materials (brick, cement), regarded as a social symbol of modernity, cob fell into disuse [22,59,150,163,209,212,244,264].

Finally, political decisions also had a great influence on cob construction. For example, the old regime land law in Brittany [164,197,199] and an old tax on bricks in the United Kingdom [117] supported cob construction sector. On the contrary, building regulations were established without regard to cob, which was a major obstacle to the development of the sector [13,152,163,252,253]. Building regulation is still an obstacle for modern earth construction [1].

4.1.4 The future of cob process

Vernacular cob construction has many environmental, social and health benefits and is, therefore, a source of inspiration in order to reduce the impact of the modern building sector. Nonetheless, this slow process was time-consuming and required a large workforce, which is inappropriate in Western modern economies [18,19,31,34,297]. In order to comply with this economic constraint, two options can be identified for cob: the recourse to self-build houses or the recourse to mechanisation and/or prefabrication (section 4.1.2). Self-builders have little site equipment and usually use the vernacular, low-impact, process. This solution may, however, satisfy only a small part of housing needs. The other solution is to go on with the development of mechanized/prefabricated cob process. These processes may, however, consume more energy and fewer workforces than the vernacular one, thus reducing environmental and social benefits.

The cob material source is another issue since earth is a natural material and varies from a site to another. To overcome these variations, two different approaches are observed: (1) adapt the material to the process, thanks to a granular correction [12,121], forcing its particle size distribution into a grading envelope predetermined in the laboratory and/or addition of hydraulic binder [4,33,298,299], this solutions reduce the environmental benefits of cob [1]; (2) adapt the process to the material [1,34,300], this solution optimizes the consumption of natural resources and relies on the expertise of skilled craftsmen, architects and on performance based tests. It, therefore, requires the education of specialist of cob construction.

Cob, like other earth construction process, encounters a renewed interest thanks to its low environmental impact. However, the economic and regulation constraints of the building sector impose to speed up the construction process and to strengthen the material, which reduces environmental and social benefits. A balance has to be found between a zero-emission vernacular material and a fast implemented and strengthens the material. The future of earth construction will be the result of an optimization of the economic and environmental sustainability of construction processes.

4.2 Performance based approach

The placement of construction products in the European Union market is set by the Construction Products Regulation [301]. This regulation enforces manufacturers to provide the characteristics of their products in a Declaration of Performance and to label their product with CE marking. This prescriptive approach is well adapted to standard industrial products but not to natural, variable, non-conventional materials [293]. This regulation constraint led several authors and producers to propose to standardise earth materials: by granular correction and admixture addition or by exploitation of earth quarries. However, these solutions alter the beneficial impact of earth buildings. Since the use of earth, with regard to conventional material, is legitimated by its low impact, these solutions are deemed as irrelevant for earth construction sector in a long term perspective.

Another solution is the elaboration of performance based procedures [57,253,293,302]. The aim of this approach is to validate the performance of building elements thanks to specimens manufactured on-site. This approach requires the assessment of the performance of any new building. Regardless of the material, the formulation and the implementation technique, the real performance of building elements is assessed. Thus, performance based approach allows using any kind of earth and process, and more specifically local raw earth implemented with low-embodied energy construction technique. It also avoids standardisation of the construction process and contributes to the preservation of the diversity of local construction cultures. This approach thus covers all the needs of the earth construction sector and is the only one enabling the validation of the most sustainable earth building solutions. Two different performance based laboratory procedure are proposed here, one for plasters on earthen walls (section 4.3) and another one for cob walls (section 4.4).

4.3 Plasters

4.3.1 Introduction

Plasters maintenance of earth heritage is a major issue in order to preserve this heritage. Unfortunately, old construction techniques fell into disuse in the West and are therefore no longer practised by the vast majority of masons. Industrial cement-based coatings are unsuitable and may even be harmful to earth constructions [303,304]. As part of a working definition of a code of practice for using plaster on earthen walls [305], a research campaign was conducted to validate on-site tests to select suitable plaster formulations. These results were published in 2013 in [306].

In France, the maintenance of outside plasters to ensure built heritage is principally achieved with lime/sand renders. These plasters are quite commonly used for stone walls, and their formulations and implementation techniques are well known by masons. Lime and sand plasters are compatible with earthen walls, but earth plasters have also been traditionally used on earthen walls [305]. Earth/sand renders are mainly used as inside plasters. For outside plasters, earth/sand renders are added to admixtures that limit the effects of weathering. Unfortunately, in France, masons no longer practised earth plaster formulations and implementation techniques. Thus, this study mainly investigates earth plasters but also includes lime/sand plasters. The proposed procedure is designed for France. It may need some adaptations to be used in other countries, according to climate (high rainfalls for example) and chemical composition of soils (presence of salts for example).

Earth plasters feature two advantages: they are permeable to water vapour, and their mechanical behaviour is similar to that of earthen walls, which make them more compatible with earthen walls than cement based coatings, which are waterproof and overly stiff [189,303–305]. The mechanical compatibility can be estimated based on the difference between Young's moduli of the wall and plaster; if there is too large of a difference, the stress changes induced by overloads, moisture and temperature variations generate a differential strain between the plaster and wall leading to damage to the plaster or earthen wall. The Young's Modulus of the earthen wall (approximately 0.5 GPa for rammed earth [307]) is significantly lower than the concrete Young's moduli (ranging from 15 to 50 GPa). Thus, earth and lime/sand plasters [308], with Young moduli ranging from 1 to 10 GPa, are well adapted to earthen walls *a priori*.

Earth plasters are made from earth excavated near the building site; a certain amount of sand is then added to these earths. As masons did for centuries, numerous admixtures (e.g., vegetable and animal fibres, soap, milk, fresh cow dung and red wine) can be added to these two bases to improve their properties [309–312]. Unlike standardized building materials, earth materials vary considerably. It is impossible to determine a formulation that is suitable for all sites; therefore, based on tests already carried out by masons, the field tests in this study are proposed to validate plaster formulations in terms of properties of each type of materials used. This approach is designed to allow the choice of materials at the discretion of masons, thus promoting the use of local materials and respecting local construction cultures.

An earth plaster is of acceptable mechanical quality if, after shrinkage, there are no cracks through which water can penetrate into the wall, and the plaster has a sufficient bond with the wall. In this study, two on-site tests (a shrinkage test and a shear test) were conducted to validate the plaster formulations. A testing campaign was conducted to validate these two tests. The proposed tests were applied to plasters made from two different earth. Additional laboratory tests were conducted to measure the methylene blue value, shrinkage, bending strength and water content of these plasters.

4.3.2 Experimental procedure

4.3.2.1 Earthen wall preparation

In the first testing campaign, an old rammed earth house located in Chamboeuf (France) on real on-site conditions was used. This house was rendered with a lime/sand plaster. In this case, only the lime/sand plaster was studied. In the second testing campaign, an outdoor cob wall located in a farm garden belonging to the *Grand Parc de Miribel Jonage* in Vaulx-en-Velin (France) was used. This wall was composed of a basement of slag concrete that underpinned a cob rising of approximately 500 mm. Non-professionals constructed this wall under bad weather conditions; therefore, it is quite eroded and seems to be of poor quality. In the third testing campaign, stabilized rammed earth walls realized in the laboratory were used. The two rammed earth walls have a smooth wall surface. The cob wall and the rammed earth walls were brushed and repeatedly wetted with a garden sprayer. For the second and the third testing campaigns, a scratch coat consisting of 1 volume of Natural Hydraulic Lime (NHL 3.5) and two volumes of Hostun sand [313] (maximum diameter of 0.8 mm) was thrown on the earthen wall. To limit the impact of the scratch coat on results, the same lime and sand were used, with approximately the same amount of water to get the same consistency and it was always implemented by the same operator. However, the scratch coat is irregular and may have an impact on the scattering of the results. This scratch coat ensures a better key of plaster on the wall. Earth plasters are applied directly to this scratch coat. This is the traditional French way of preparing an earthen wall prior to coating [305].

4.3.2.2 Testing campaign

Earth plasters were prepared from earths (e.g., clays, silts and sand) to which variable proportions of sand and water was added. Clay fraction plays the role of binder and is responsible for the shrinkage of the plaster. Silt and sand constitute the granular skeleton that makes up the mechanical structure of the plaster.

According to masons, a good earth plaster formulation must contain enough clay to bind the entire granular skeleton and prevent its erosion but not too much to limit its shrinkage. Therefore, an earth:sand ratio by volume or by mass that will not generate harmful plaster shrinkage and will allow sufficient sand grain covering is typically sought. In this study, shrinkage is considered to be harmful if it causes deep cracks or a delamination of the plaster; crazing is not considered injurious. To validate their formulations, masons typically conduct on-site tests, which differ from one mason to another. Because of the definition of a new code of practice, which involved more than 60 earth construction professionals under the coordination of the French network "*écobâtir*", it has been possible to propose a standardized procedure. This procedure consists of a shrinkage test followed by a shear test.

The shrinkage test requires a 250x250 mm sample of each formulation of brown coat. The number of layers and the thickness of the specimens should be the same as those for the final plaster. For the testing campaign, specimens had 2 layers and a total thickness of approximately 20 mm. After drying, when shrinkage is completed, the presence or absence of cracks in the samples was noted. Only samples without cracks are validated.

A second important aspect of earth plaster formulations is their bond to the wall. This bond depends on the nature of the wall (e.g., materials, material implementation and possible heterogeneities), the wall's hydric state and the nature of the plaster.

The aimed dimensions of the shear test specimens are 50 mm × 40 mm × 20 mm. As it is impossible to obtain specimens with those exact dimensions, all specimens were measured before testing. For the first testing campaign on the cob wall, there were 2 specimens of each formulation. Unfortunately, the results were too scattered to be meaningful, which is why a second testing campaign on a rammed earth walls was undertaken. In this second campaign, there were 5 specimens of each formulation. The samples were loaded until failure with a loading device (Figure 47) by increments of 0.5 kg for Tassin earth samples and for reasons of precision, by increments of 0.25 kg for the other samples. At first, the duration of the test was 60 s. Since all sample failures occurred in the first 10 s it was decided to reduce the duration of the test to 30 s. An example of loading device is given in Figure 47. This loading device is not standardized and different kind of loading devices can be used. Nevertheless, the loading device must ensure a good contact with the top of the specimen and minimize the contact with the wall.

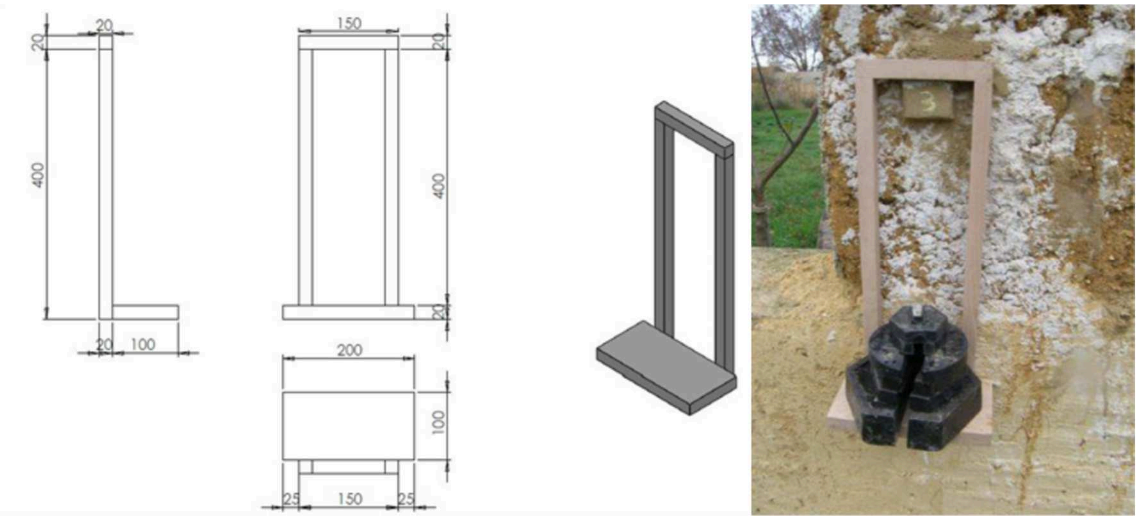


Figure 47. Shear test loading device example, 400 mm high, 150 mm large and 20 mm thick.

The mass at which the sample breaks, which is called failure mass (m_f, kg), was recorded. Based on the loads and surface of the sample (S, mm^2), it is possible to calculate the average shear stress (τ, Nmm^{-2}) as

$$\tau = m_f.g / S \qquad (16)$$

where g = 9.81 m.s^{-2}.

The following additional laboratory tests were carried out to better characterize the earth plaster:

- The Methylene Blue Values (MBVs) of the Tassin and Rochechinard earth were measured using the French standard NF P 94-068 [290] (Table 14). The MBV measures the water sensitivity of a soil, which is largely related to the amount and nature of the clays of the earth.

- Plaster's longitudinal shrinkage for samples of 40×40×160 mm was obtained by measuring the length of the specimen, thanks to a ruler, before and after drying. Two specimens were measured for each formulation;

- Three-point bending test on 2 plaster samples of 40×40×160 mm per formulation was performed. The maximal force reached (F, N) was recorded, and the bending strength (σ, Nmm^{-2}) was calculated as

$$\sigma = \pm 3F.d/(2.w.h^2) \qquad (17)$$

where: d (mm) is the distance between lower supports points, w (mm) is the width of the specimen and h (mm) is the height of the samples.

*Table 14. Characteristics of the Tassin and Rochechinard earths (*MBV = Methylene Blue Value)*

Earth	Clays < 2 µm	2 µm < silts < 20 µm	20 µm < sands< 2000 µm	MBV*
Tassin	18 %	12 %	70 %	1.4
Rochechinard	26 %	32 %	42 %	2.5

4.3.2.3 Sample production

Tassin and Rochechinard earth were used for the tests [314] (Table 14). Since Rochechinard earth has a 26 % clay content and Tassin has a 18 % clay content [314] (Table 14), five different clay contents of 18%, 12%, 9%, 6% and 3% in dry weight were reached by adding Hostun sand to those earths (Table 15).

Table 15. Plasters formulations used for the testing campaign together with the water content of the plasters at the time of their application and their curing time. An abbreviation is used to name each formulation, where the letter specifies the earth used (T = Tassin, R = Rochechinard), the number corresponds to the clay content (18/12/9/6/3) and an admixture (if used) is specified with a + (H = Hemp Chaff, S = Sisal).

	Tassin				**Rochechinard**					**Rochechinard with admixtures**			
Sample name	T18	T12	T9	T6	R18	R12	R9	R6	R3	R18+S	R12+S	R18+H	R12+H
Clay content by mass (%)	18	12	9	6	18	12	9	6	3	18	12	9	6
Mass of earth (kg)	5	3.43	2.57	1.71	3.43	2.35	1.76	1.18	0.59	3.43	2.35	1.76	1.18
Mass of sand (kg)	0	1.57	2.43	3.29	1.57	2.65	3.24	3.82	4.41	1.57	2.65	3.24	3.82
Sisal (g)	-	-	-	-	-	-	-	-	-	25	25	-	-
Hemp chaff (g)	-	-	-	-	-	-	-	-	-	-	-	25	25
Amount of added water (L)	1.35	1.18	1.02	1.14	1.26	1.14	1.25	1.24	-	1.36	1.20	1.28	1.12
Water content on the cob wall (%)	27	24	20	23	25	23	25	25	-	27	24	26	22
Curing time on the cob wall	38 days				37 days					20 days			
Amount of added water (L)	-	-	-	-	-	1.03	1.13	1.23	1.33	-	-	-	-
Water content on the rammed earth blocks (%)	-	-	-	-	-	21	22	25	27	-	-	-	-
Curing time on the rammed earth blocks	-	-	-	-	-	14 days		55 days		-	-	-	-

The Rochechinard earth plasters with 18% and 12% clay contents were also tested with Sisal fibres [315] and hemp chaff aggregate [316] (Table 15). The samples contained an admixture amount of 0.5% by dry weight of mortar, which is a classical value [317] and which corresponds to 25 g by formulation. Sisal fibres are much finer and longer than those of hemp chaff (Sisal: diameter: 0.15 mm, length: 40 mm; hemp chaff: rectangular section: 2 × 5 mm, length: 20 mm) [315,316]. The number of elements per gram is also much higher in Sisal fibres than in hemp chaff.

Finally, a lime/sand plaster composed of 1 volume of lime (0.5 % calcic lime CL and 0.5 % hydraulic lime NHL 3.5) and 3 volumes of Hostun sand was also tested as a reference.

Before sample production, earth and sand were placed in an oven at 105°C and were considered to be dried after 72 h. Then, earth/sand mixtures were manufactured at the appropriate proportions, dry mixed in the laboratory and were bagged to maintain dryness. The water amount considered necessary to obtain a good workability of the mortar was added on-site. This amount of water was measured, and the water content of the mortar was calculated (Table 15).

4.3.3 Results and discussion

4.3.3.1 Shrinkage test

Lime/sand shrinkage test specimens do not exhibit any damages. As shrinkage has more dramatic effects on earth based plasters than on lime/sand ones, this section focuses on earth based plasters.

The results of the 250×250 mm squares shrinkage test are presented in Figure 48. Tassin and Rochechinard 18% clay plasters fell off the wall; those with 12% clay cracked, and those with 9% and 6% clay did not crack. The plasters with 6% clay were very sandy, making them more difficult to work with and relatively powdery after drying. The optimal clay content, in this case, is approximately 9%. Clay content has a clear influence on earth plaster cracking. These results are consistent with shrinkage measurements made with the 40×40×160 mm specimens of the 3-point bending strength (Figure 49): the higher the clay content the greater the shrinkage. This is also consistent with the observations made by Kouakou et al. for earth mortars and adobes [70].

Tassin and Rochechinard earth have similar workability and shrinkage test results for the same clay content. This observation is consistent with the MBV of those earths (Table 14), which are of the same order of magnitude. Those two earth have a similar capacity of water adsorption.

The addition of Sisal fibres to the Rochechinard earth with 18% and 12% clay greatly improves the workability of the mortar. Although the mortar tends to delaminate, the cracking of the mortar is significantly reduced because the 18% clay plaster without fibre, which fell from the wall, shows no cracks with a 25 g Sisal addition. The 12% clay plaster with Sisal fibres was validated, while the one without fibres was not. This beneficial role of fibres such as Sisal (limiting damages linked to earth plaster shrinkage) has already been reported in the literature for earth mortars and adobe walls [311,315,317,318].

The Rochechinard earth combined with 25 g of hemp chaff aggregate has a similar workability to that without fibres. Thus, the addition of 25 g of hemp chaff does not improve the workability of the mortar. The shrinkage causes the delamination and some cracks in these plasters (R18 + H and R12 + H). Even if cracking is less important for plasters with hemp chaff than for those with earth, none of those plasters could be validated. The effect of 25 g of Sisal in earth plaster is more beneficial than that of 25 g of hemp chaff.

Tassin	Rochechinard	Rochechinard with admixtures
 **T18** Cracked: - Delaminated: - Fallen: Yes	 **R18** Cracked: - Delaminated: - Fallen: Yes	 **R18 + S** Cracked: No Delaminated: Yes Fallen: No
 **T12** Cracked: Yes Delaminated: No Fallen: No	 **R12** Cracked: Yes Delaminated: Yes Fallen: No	 **R12 + S** Cracked: No Delaminated: No Fallen: No
 **T9** Cracked: No Delaminated: No Fallen: No	 **R9** Cracked: No Delaminated: No Fallen: No	 **R18 + H** Cracked: Yes Delaminated: Yes Fallen: No
 **T6** Cracked: No Delaminated: No Fallen: No	 **R6** Cracked: No Delaminated: No Fallen: No	 **R12 + H** Cracked: No Delaminated: Yes Fallen: No

Figure 48. Shrinkage test results. The validated formulations here are T6, T6, R9, R6 and R12 + S.

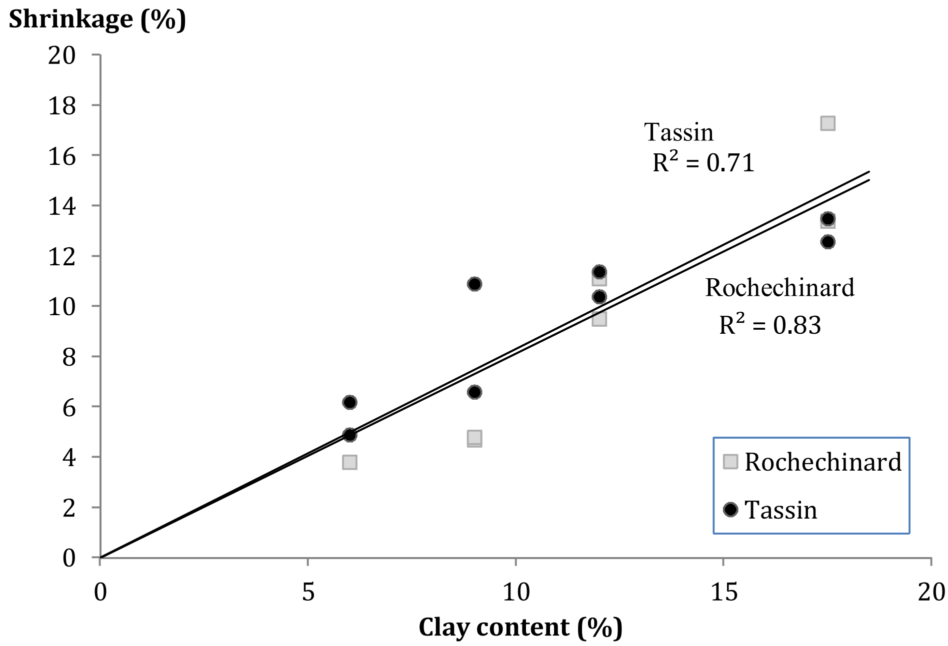


Figure 49. Influence of the clay content on the longitudinal shrinkage of 40×40×160 mm samples. A zero shrinkage is assumed for the 0 % clay content.

The shrinkage test allows finding the earth plaster formulations. Among all the validated formulations, the mason chooses the best one thanks to two criteria: the best workability (which is variable according to masons) with the highest clay content as possible. This test is more relevant for earth plasters than for lime plasters which need less water to obtain the right consistency. Based on the experiences of the different masons, a final protocol can be proposed. To be sufficiently representative, the test has to be carried out under conditions closest to those of the real on-site implementation. First, prepare the wall to be coated as it will be for the real coating. Next, apply a brown coat sample of at least 250×250 mm for each formulation on the wall to be coated. Shrinkage specimens must be the same number of layers and the same thickness as the predicted coating. To validate a formulation, the sample should not fall, crack or delamination. The most argillaceous formulations offer a better resistance to erosion and should be favoured. The test results remain valid only if the plaster is carried out on a wall in a state (brushing and humidification) similar to that during the tests.

4.3.3.2 Three-point bending strength

The lowest bending strength of the campaign was that of the lime/sand mortar (Figure 50). This is because the very fine Hostun sand (maximum diameter of 0.8 mm) used in the samples did not provide enough structure to the plaster. Furthermore, there was an insufficient time lapse between the manufacturing and testing of the sample (1 month) to enable a good setting of the NHL.

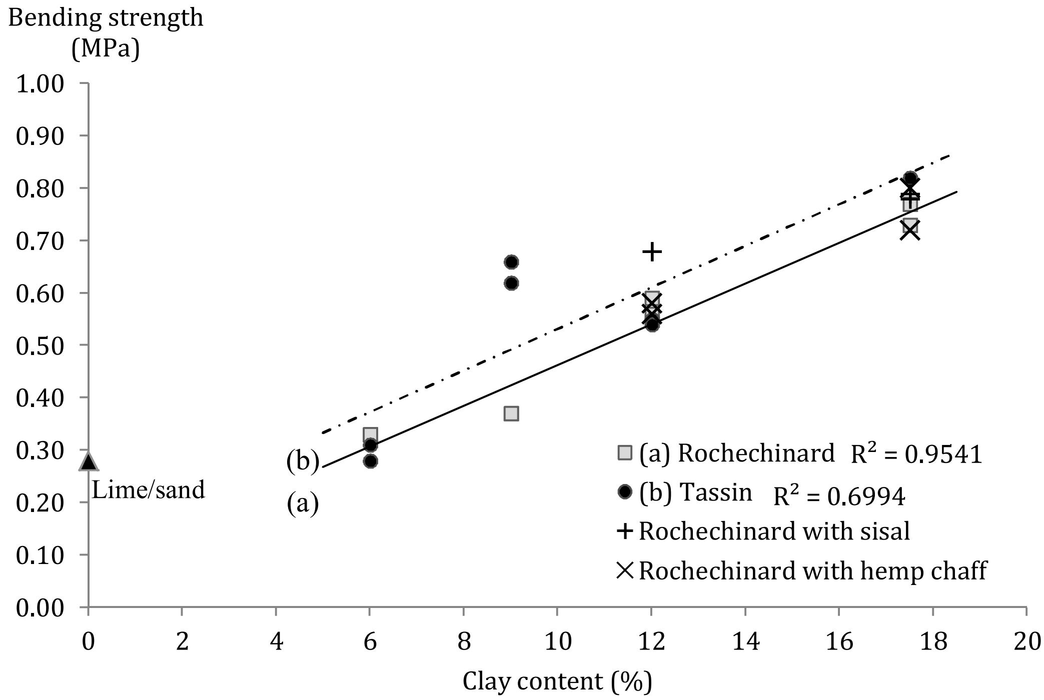


Figure 50. Influence of the clay content on the 3-point bending strength

The bending strength of the Tassin and Rochechinard earth mortars increase with clay content (Figure 50). An increase in the amount of clay of the 40×40×160 mm specimens increases the amount of binder in the mortar, which in turn increases the shrinkage of the specimen. A greater shrinkage will provide a higher dry density of the specimen and therefore a higher mechanical strength [309]. This finding contradicts the shrinkage test results, which showed that an increase in the clay content weakened the plaster. This contradiction is partially due to the size of specimens. Because the shrinkage test specimens are larger and thinner than those used to determine the bending strength, the effect of shrinkage will be more dramatic on the shrinkage test specimens. The contradiction also arises from the implementation of the specimens. The bending strength specimens are free to shrink, whereas a side of the shrinkage test samples is bonded to the wall; this generates a differential shrinkage between the side of the specimen linked to the wall and the opposite side. If this differential shrinkage is too high, it produces cracks in the plaster. The same phenomenon occurs when earth plasters are implemented over the entire surface of a wall. The shrinkage test thus reflects the reality of on-site conditions.

The bending strength of the plasters with admixtures is similar to that of the earth plasters (Figure 50). [317] have shown that fibre-reinforced earth blocks have a tensile strength similar to that of plain earth blocks, but fibre-reinforced earth blocks have a higher ductility in tension and thus further limit the propagation of tensile cracks [315,317].

4.3.3.3 Shear test

In the proposed protocol only the formulation validated by the shrinkage test might be tested. For the need of the research campaign, the shear test was conducted for all formulations.

Figure 51 shows a comparison of the shear strength results versus the clay content of the Rochechinard plasters on the cob wall and those on the rammed earth walls. As the clay content increases from 0 to 6 %, the shear strengths of the Rochechinard plasters on the cob wall and rammed earth walls increase. Then an increase in the clay content beyond 6 % leads to a decrease in the shear strength. Thus, Rochechinard earth plasters on both the cob wall and rammed earth walls exhibit an optimum shear strength depending on the clay content (Figure 51).

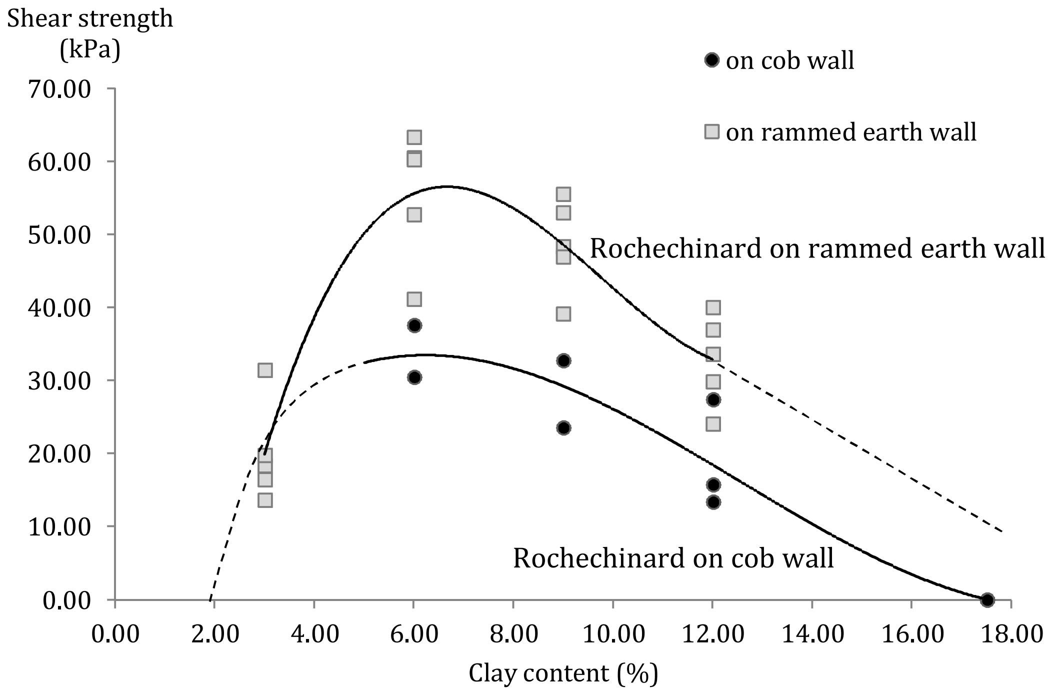


Figure 51. Shear strength vs. clay content of the Rochechinard specimens from the cob and rammed earth walls. Rochechinard data from the rammed earth blocks and cob wall are represented using a 3-degree polynomial function. As the 18 % clay content shrinkage specimen had fallen from the cob wall, the shear strength is assumed to be zero.

As shown in Table 16, the Tassin earth plaster shear strength ranges from 14 to 28 kPa for a clay content of 6 %. It rises to 35 to 47 kPa for the 9 % clay content and finally decreases to 10 to 18 kPa for the 12 % clay content. Thus, the Tassin earth plasters on the cob wall also exhibit an optimum shear strength that depends on clay content.

Table 16. Shear test results – Tassin and Rochechinard with admixtures

		Shear strength (kPa)				
Clay content (%)		Tassin	Rochechinard with hemp chaff		Rochechinard with sisal	
18	0	0	22	16	20	-
12	18	10	28	20	29	25
9	47	35	-	-	-	-
6	28	14	-	-	-	-

The optimum shear strength relationship with clay content is consistent with the observations made above for the shrinkage and bending tests (section 4.3.3.1 and 4.3.3.2). An increase in the amount of clay reinforces the plaster until the effect of shrinkage becomes predominant and decreases the shear strength (Figure 51).

The shear strengths of the plasters with admixtures are of the same order of magnitude as those of their counterparts without admixtures (Table 16). However, this results are too few and should be only regarded as a tendency.

For each formulation, the Rochechinard plasters applied on the rammed earth walls had shear strength approximately twice as large as those applied on the cob wall (Figure 51). After the shear tests, all of the failures on the cob wall occurred at the site of attachment to the wall, while the failures on the rammed earth walls occurred inside the plaster. When the wall surfaces were brushed during their preparation, it was apparent that the cob wall was easily eroded, while the rammed earth walls were quite solid. The shear strength of a given plaster depends on the nature of the wall on which it is applied.

The first testing campaign, with lime/sand plasters on a rammed earth house, gave shear strengths of 8 and 10 kPa. Those two lime/sand specimens failed by snatching part of the wall. Those low values are due to the small resistance of the wall, indicating that the shear test is also necessary for lime/sand plasters.

For the cob wall, the optimum clay content corresponding to the maximum shear strength for plasters is approximately 9 % clay for Tassin earth and 6 % clay for Rochechinard earth (Table 16, Figure 51). For a given wall, the shear strength of a plaster depends on the nature of the earth used.

The shear strength results are quite scattered, which is attributable to the heterogeneities of the earthen walls. Therefore, the shear strength of a plaster needs to be tested on different parts of the wall.

Each combination plaster-wall to be coated will have a different behaviour according to the nature of the materials, their implementation and the heterogeneities of the wall. Thus, proposing an on-site shear test with at least 5 specimens to validate plaster formulations is important. The purpose of the shear test of earth plasters on earthen wall is to ensure a sufficient bond between the plaster and its wall. It is not necessary to seek the optimum shear strength on-site; instead, it is sufficient to find a position above a safety threshold. The thickest plasters observed in France by masons are approximately 60 mm [305]. Using a safety coefficient of 10, the load exerted by a 600-mm thick plaster on a 50×40 mm sample is 20 N (600 mm × 50 mm × 40 mm × 1.7 10^{-6} $kg.mm^{-3}$ × 10 $kg.N^{-1}$ ≈ 20 N). Thus, a safety threshold of 20 N is assumed.

In this section, the final protocol for the shear test is proposed. First, prepare the wall to be coated as it will be for the real plaster. Next, apply at least five (50x40x20 mm) brown coat samples for each formulation on the wall to be coated. At least 2 samples must be on an interface, and at least 2 samples must be in the middle of an element (e.g., adobe, rammed earth, or cob layer); each sample tests a different element or interface. When samples are dry, load them with a 20-N mass for 30 seconds. An example of loading device is given in Figure 47. If all of the specimens resist the 20-N load for 30 seconds, then the formulation is validated. The test results remain valid only if the plaster is carried out on a wall in a state (brushing and humidification) similar to that during the tests.

To ensure that the shear test samples are dry, a solution is to carry out shear and shrinkage specimens at the same time. Once the shrinkage test samples have completed their shrinkage, it means they are dry. Then the shear test samples are also dry.

4.3.4 Plaster performance based procedure - Synthesis

This study proposes an experimental procedure to assess the suitability of plasters to protect vernacular earthen architecture. As earthen walls and earth for plastering show important variations, plaster formulations have to be validated through on-site tests. Shrinkage and shear tests of plasters on earthen walls are proposed here. The shrinkage test eliminates formulations beyond a shrinkage threshold specific to the plaster-wall combination and enables to find the best plaster formulation. Then the shear test validates this formulation if it offers sufficient adherence and thus sufficient shear strength of the plaster-wall interface. In addition, the use of this procedure has clarified some of the mechanisms that govern the behaviour of the plaster-wall bond.

The existence of an antagonistic control of the bond between earth plasters and earthen walls by clay content was highlighted in this study; specifically, an increase in plaster clay content results in a better bending strength, which strengthens the plaster but increases shrinkage, which may weaken the plaster-wall interface. Failures are caused by differential shrinkage between the plaster and the wall. There is an optimum clay content that mechanically matches an optimum shrinkage.

Since its publication in 2013, the article presenting these results [306] has been cited 31 times (Table 17). The article is cited mostly to provide context information [30,319–333] or to use its results for discussion purpose [184,269,334–341]. Nonetheless, 5 publications used the proposed procedure for plaster suitability assessment [341–345].

Table 17. Citations list of [306]*, 16 publications cite the article to provide context information (Context), 10 to discuss their own results (Discussion) and 5 employed the proposed protocols (Shrinkage and/or shear tests)*

Reference	Context	Discussion	Protocol employed	
			Shrinkage test	Shear test
[323]	■			
[346]		■		
[339]		■		
[30]	■			
[327]	■			
[329]	■			
[333]	■			
[322]	■			
[341]				■
[320]	■			
[184]		■		
[343]			■	■
[334]		■		
[342]				■
[345]			■	■
[324]	■			
[330]	■			
[337]		■		
[332]	■			
[328]	■			
[319]	■			
[321]	■			
[335]		■		
[269]		■		
[338]		■		
[344]				■
[331]	■			
[326]	■			
[325]	■			
[336]		■		
[340]		■		

Results of plaster shrinkage test were presented only in [343,345]. In [345] a 9% unfibered clay plaster formulation was validated, which is in good agreement with our results (section 4.3.3.1). No specific comments concerning this test can be found in the literature. It can be therefore be deemed as a suitable test.

Shear tests were carried out with earth plasters [341–345], earth-fibre plasters [341–345] and earth plasters stabilized with gypsum [343,344], lime [343,344] and other admixtures [345]. For any of the tested formulation, shear test results allowed a clear discrimination of plaster formulations with high and low adherence to the wall. In [345] plaster adherence was higher on rammed earth wall than on cob wall, and both exhibited optimum clay content (Figure 52). These findings are in good line with our results (section 4.3.3.3, Figure 52). Nonetheless [342–344] noticed that results scattering was high and they recommend to increase the size of shear specimens. Moreover, [342–344] also highlighted the difficulty to carry out small plaster test specimens.

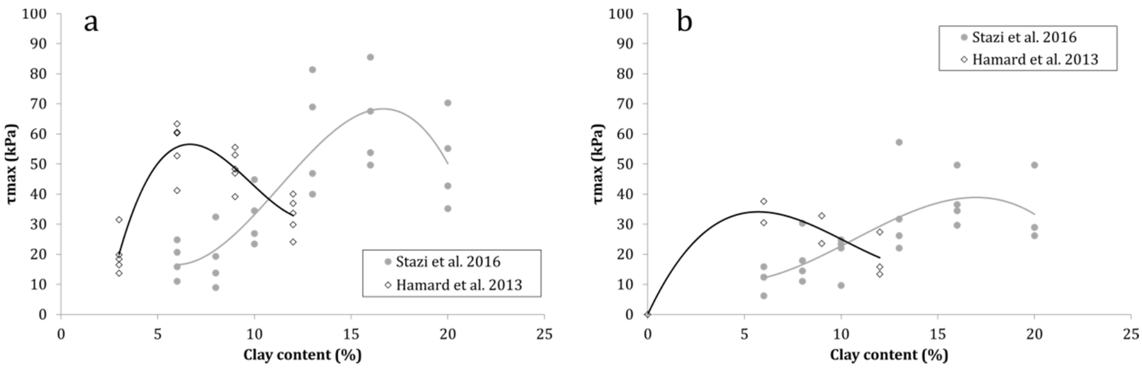


Figure 52. Comparison of shear test results of [306]*and* [345]*performed on rammed earth wall (a) and cob wall (b)*

The DIN 18947 [347] test procedure is also employed to validate the bonding of earth plasters on walls. The DIN 18947 standard refers to the EN 1015-12 [348] "pull off" testing procedure and sets strengths classes. The strengths classes are deemed as unsuitable [342] and the "pull off" test failed to give a full account of in-situ conditions [341,342,346]. Instead, they recommend the shear test proposed here.

The plaster performance test procedure, proposed in 2012, is part of the French code of practice for earthen wall plastering [305]. This code of practice has been validated by the French inter-professional insurance authorities and is routinely used by earth masons. It is also applied by several laboratories for research purpose. This procedure set a precedent to promote the use of performance based approach in earth construction. However, plasters do not play any building structural role. The application of the performance based approach for a load-bearing material is another challenge. This is discussed in the next section for cob.

4.4 Cob

4.4.1 Introduction

Cob is a vernacular earth construction technique, which consists in realizing earth elements in a plastic state, implemented wet and stacked in order to build a monolithic and load-bearing or freestanding wall (section 1.4.1). A significant cob heritage exists in Europe, Africa and Asia and require appropriate maintenance and characterization (section 3.3.1) [22,120]. Moreover, like other earth construction techniques, cob encountered a renewed interest in modern sustainable building for its low environmental impact in comparison to conventional construction materials (section 1.1.5) [1,31]. The development of a performance based procedure to validate cob walls is a major issue (section 4.2).

Cob construction is carried out with highly wetted soil material, kneaded by foot and piled in the wall at plastic state. These mixing and compaction methods generate an irregular kneading and are original in the context of soil mechanic. This particularity of cob material requires the development of a suitable laboratory testing procedure to assess its mechanical performance.

Before presenting the new laboratory procedure, a review of cob mechanical behaviour literature is proposed in section 4.4.2.

4.4.2 Cob mechanical behaviour review

4.4.2.1 Laboratory procedures

Uniaxial Compressive Strength (UCS) and Young's modulus (E) determination are the most commonly cited tests for cob mechanical behaviour characterisation. Specimens' fabrication procedures for the determination of UCS and E refer to cylindrical test specimen with a slenderness ratio of 2:1 in order to reduce the frictional forces due to the confinement caused by testing machine plates [15,22,91,115,120,252]. Specimens' sizes are either 100×200 mm or 150×300 mm since smaller size specimens are judged unrepresentative and larger ones are too heavy to be handled conveniently [22,91,115,120]. Cob mixture was implemented inside cylinder moulds in several layers and compacted: (1) under dynamic load thanks to a Proctor compaction device [22,91,115,120] or (2) placed by hand [15]. Cob mixture was also implemented inside cylinder moulds by compaction under static load thanks to a machine [252]. The aim during compaction was to produce specimens that did not contain noticeable air voids. As the cob mixture is in a soft state, overcompaction would have little additional effect on the density [120].

Specimens are air-dried [22], dried in a humidity and temperature controlled chamber (25°C and 75% relative humidity) [91,115,120] or oven-dried (75°C) [15]. Oven drying can affect suction and therefore lower the mechanical strength of earth materials [119]. Moreover, natural fibres are subjected to temperature decay. Usual recommendations impose a drying temperature lower than 60°C. Moreover, the mechanical strength of earth materials depends on the water content of the specimens: the higher the moisture content, the lower the compressive strength [120,349,350]. For repeatability reasons, specimens should be conditioned in a humidity and temperature controlled chamber until weight stabilisation prior to testing. If conditioning is not possible, the water content during the mechanical test should be recorded.

A typical cob mechanical test description is proposed by [252]. Three phases are identified (Figure 53): (1) initial compaction of the sample, (2) linear stress/strain response of the sample and (3) increasing crack growth within the sample and failure of the sample. [267]

describe the typical course of cob wallets testing as an elastic range with a low shear modulus followed by a plastic-type deformation of the specimen. In both cases, a linear stress/strain response is followed by a ductile failure, induced by fibres [115,267].

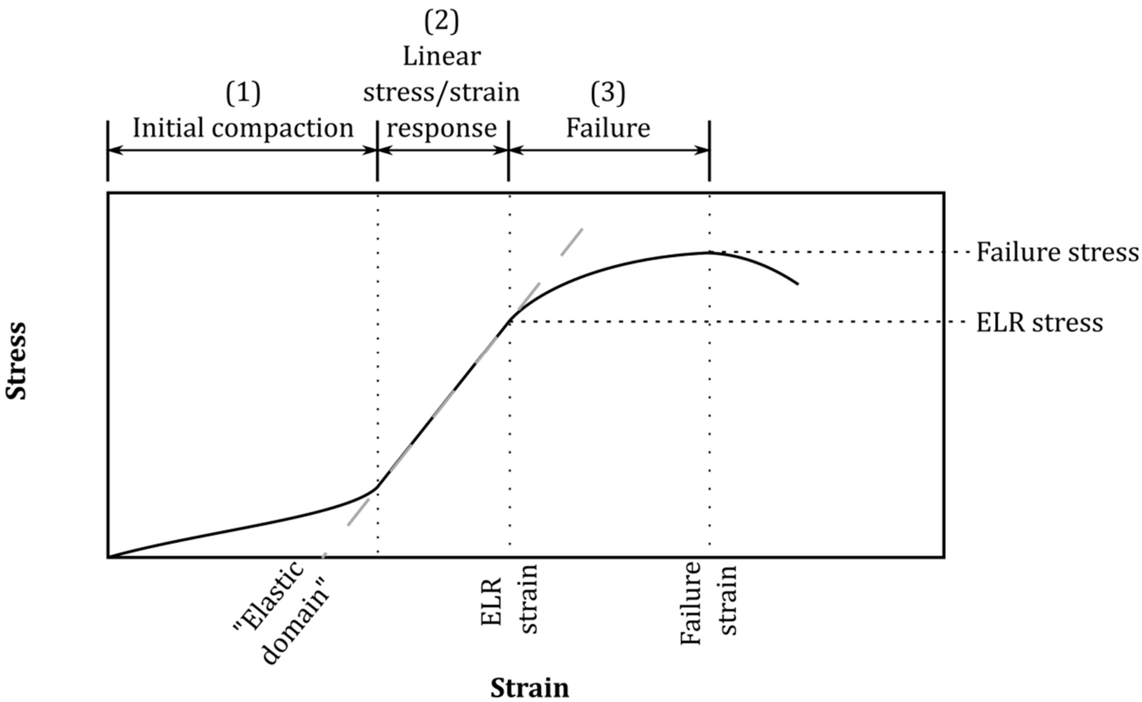


Figure 53. Typical cob Uniaxial Compressive Strength test (ELR = End of Linear stress/strain Response), after [252].

Compressive strength tests conducted on square cob wallets 500 mm side [267], nondestructive test estimating the compressive strength using a rebound hammer [12] (*Table 18*) and a four points bending strength test method [15] were also proposed.

Table 18. Corresponding value between rebound hammer display values and compressive strength, after [12]

Rebound hammer value	35	40	45
Compressive strength (MPa)	0,7	1,0	1,3

Tangent Young's moduli values proposed in the literature are calculated according to total strain of test specimens, i.e. thanks to the displacement of testing machine plates [15,115,252]. However, earth materials have an elasto-plastic behaviour [349]. As a consequence, in order to measure the elastic contribution only, secant moduli of repeated loading cycles should be considered. Furthermore, it has been demonstrated for rammed earth that frictional forces caused by confinement of testing machine plates have a high impact on E values [85]. Strain measurement for E calculation should only concern the central third part of cylindrical specimens. Most of cob data available in the literature were obtained without regard to these requirements.

Little literature exists concerning cob mechanical behaviour, and each author has developed its own testing protocol. This makes difficult data comparison and highlights a unification need for mechanical testing procedure [84,267].

4.4.2.2 Mechanical behaviour of cob mixture

Cob mixture clods are piled at plastic state to build lifts. Slenderness ratio of lifts depends on the mechanical resistance of cob mixture (section 3.3.3.2): the higher the mechanical resistance, the higher the lift and the quicker the construction process. Past builders aimed at increasing lifts height in order to save time and reduce costs. Mechanical performance of cob mixture is therefore of great interest for the economical optimization of cob process. Typical UCS of cob mixture is 0.05 MPa [91,120], which is enough to build a lift of about 2 m high [18,120].

Fibres, when added, are thought to play a major role in the mechanical behaviour of cob mixture at plastic state by enhancing its cohesion and allowing the mixture to be implemented without the use of shuttering [120]. Hence, Saxton [120] defined an optimal straw and water content domain (Figure 54) for which cob mixture is not too plastic, in order to ease cob mixture implementation, but not too dry, in order to facilitate fibre and earth mix. Fibres contribute to the distribution of drying shrinkage cracks of clayey earth, limiting disorders caused by shrinkage, but also creating fragilities that weaken the structure [22,120]. This is the reason why optimal fibre contents are proposed in the literature.

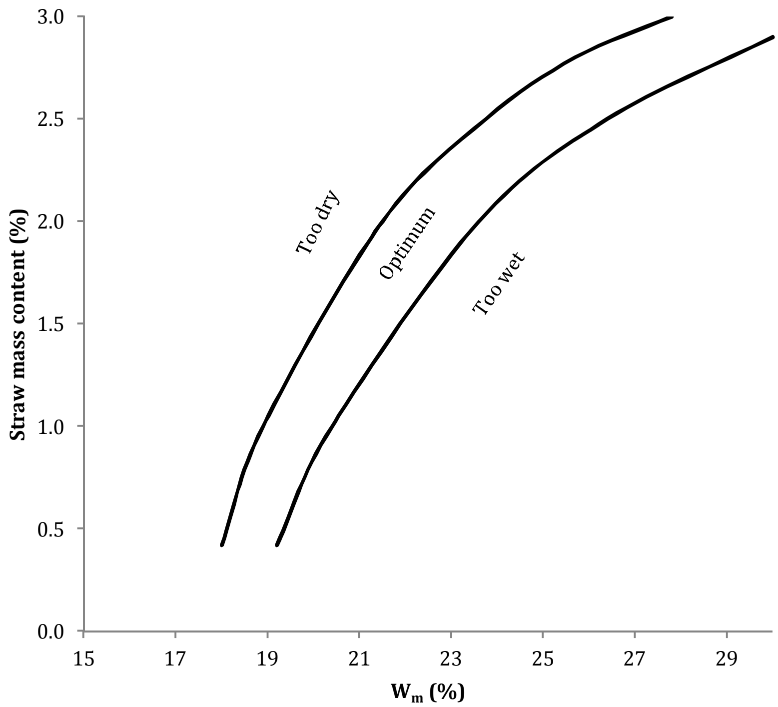


Figure 54. Optimal cob mixture with regard to water content of manufacturing stage (W_m) and straw content, after [120]

4.4.2.3 Mechanical behaviour of cob walls

Load

Ranges of cob compressive strength found in the literature are summarized in Figure 55. Compressive strength typically range from 0.6 to 1.3 MPa [12,15,22,35,115,120]. The highest compressive stresses in cob buildings are likely to be at the base of gable end walls, and under roof trusses, where wall plates help to distribute the load [120]. Keefe [22] estimates that the compressive strength at plinth level in a traditional two-storey cob house with 550 to 600 mm thick walls, ranges from 0.08 to 0.10 MPa. Considering minimum compressive strengths found in the literature (Figure 55), for cob heritage, cob compressive strength is at least five times higher than maximum compressive strength borne by cob walls [22,91,120].

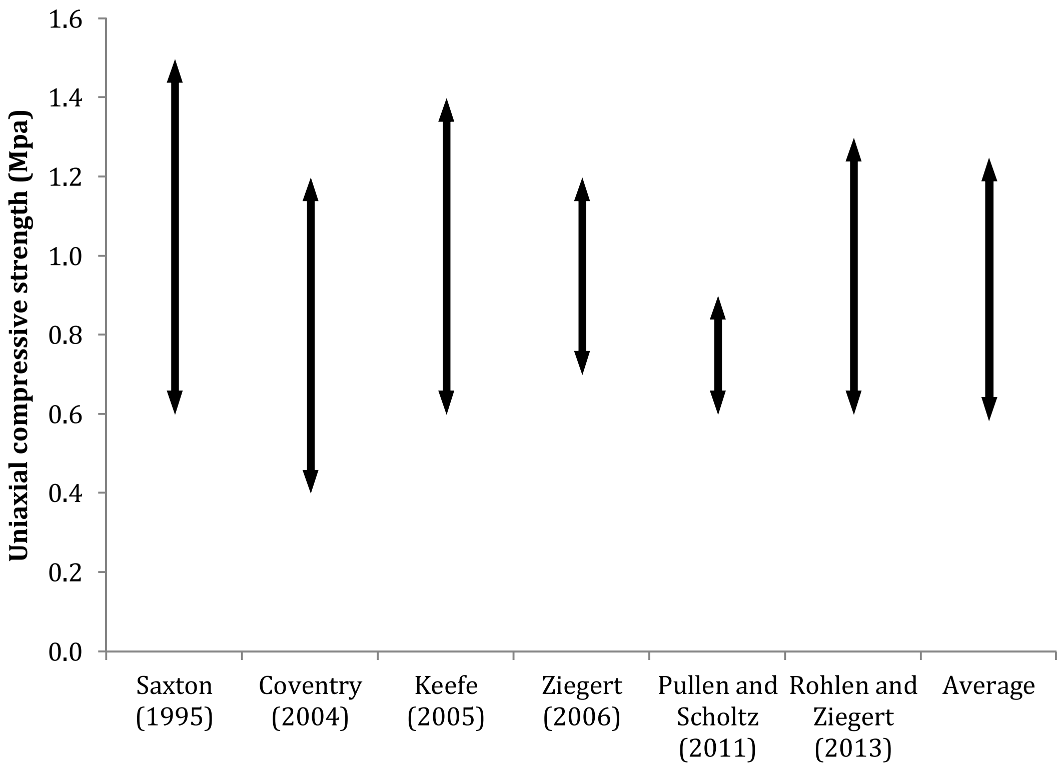


Figure 55. Range of cob compressive strengths found in the literature [12,15,22,35,115,120] *and average values.*

Texture and density

Several factors govern the mechanical behaviour of cob wall. A well-graded earth allows to maximise particles contact and enhance its mechanical strength [22]. Strength is also higher in clay-rich earths [22,251], but clay generate a more important shrinkage and can be responsible for shrinkage cracks that weaken the structure. The more the earth is compacted during implementation, the more the density and the more the strength are [22,267]. Authors agreed with a cob dry bulk density close to 1500 kg.m^{-3} [12,35,39,267].

Fibres

Although fibres were not necessarily incorporated into cob mixture (section 3.3.2.3), no data is available on unfibered cob mechanical behaviour. This can be attributed to two different reasons: firstly, for the majority of authors, cob refers necessary to fibre addition and secondly fibres are assumed to have a beneficial effect on the mechanical behaviour of cob before, during and after drying. As a consequence, all bibliographical results presented here concern only fibred cob.

The presence of fibres in cob material results in a ductile behaviour of simple compression test specimens, with large vertical strain [22,115,120,252,267]. Crack patterns after the tests are almost random and even after breaking the fibres hold together the different parts of the broken specimens [120,267].

Stiffness

The presence of fibres also induces a low stiffness of cob specimens, ranging from 170 to 335 MPa [351]. As a consequence, the contrast of stiffness with rigid construction material introduced vertically inside cob walls is responsible for damage mechanisms [12]. Same damage mechanism has been highlighted for cement-based platers, too stiff, with regard to earthen walls (section 4.3.1). The architectural design of cob buildings should avoid the use of stiff materials placed vertically against cob walls. This more specifically concerns anti-seismic design.

Moisture

Cob material is traditionally not stabilised with a hydraulic binder. Therefore, cob walls are sensitive to water content variations. When too much water enters a cob wall, the clay particles which bind it together are forced apart, and the cob is first reduced to a plastic, then to a liquid state, with consequent structural failure. There is a coupling between mechanical strength and water content [22,91,120,267] (Figure 56). Saxton [120] considered that above 10 % water content there is a major damage risk.

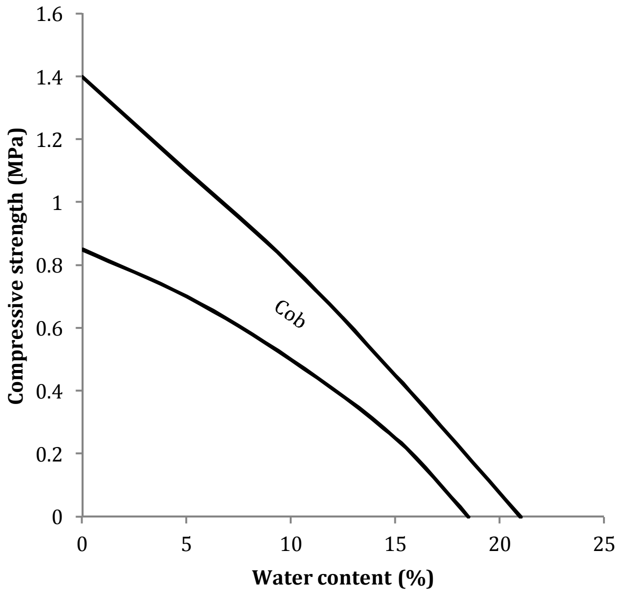


Figure 56. Variation in compressive strength against water content, after Saxton [120]

Nevertheless, Keefe [22] stated that intact soils samples removed from earth walls immediately following their collapse have shown a moisture content as low as 7 % in some cases. Keefe [22] defines a *Critical Moisture Content* (CMC). According to him, this CMC is just below the *Plastic Limit* (PL). Indeed, the plastic limit of a sample is measured using the fine fraction of the soil (< 425 µm). It is therefore only relevant to soils composed entirely of fine material. As a consequence plastic limit value has to be weighted by the 425 µm Passing ($P_{425µm}$) of the materials using the formula:

$$CMC = LP \times P_{425\mu m} \qquad (18)$$

With: *CMC : Critical Moisture Content (%), LP : Plastic Limit (%) and* $P_{425\mu m}$ *: 425 µm Passing (%)*

Usually, equilibrium water content in a cob wall ranges from 3-4% [120], which is dry enough to provide sufficient strength to the material. Since they were built without damp proof courses, moisture increase more specifically concerns cob heritage buildings. Nonetheless, majority of failures in cob walls can be attributed to either neglect, inappropriate maintenance and repair [251,352]. If well maintained by skilled craftsmen, moisture is self-regulated by the wall and cob does not pose any particular damage risk [328].

In modern cob walls, damp proof courses are generally introduced. Modern cob buildings are therefore less concerned by rising damp from the ground. If moisture issue is less significant for modern cob walls than for cob heritage walls, other moisture sources might be considered for this highly hygroscopic material [48]. As a consequence, architectural design for modern cob buildings should avoid the use of waterproof covering against cob walls (section 4.3.1).

4.4.3 Materials and methods

4.4.3.1 Introduction

In this section, an original laboratory procedure for cob sample production is proposed and tested. A flexible geotextile cover (a flexible synthetic fabric) is placed on the inner face of a cylinder mould wall (diameter 150 mm, height 300 mm) to reduce the friction and the adherence with soil (Figure 57). Cob wall elements were carried out and tested. Their mechanical characteristics are used as a reference in this study. Different laboratory procedures were tested and compared to cob wall elements.

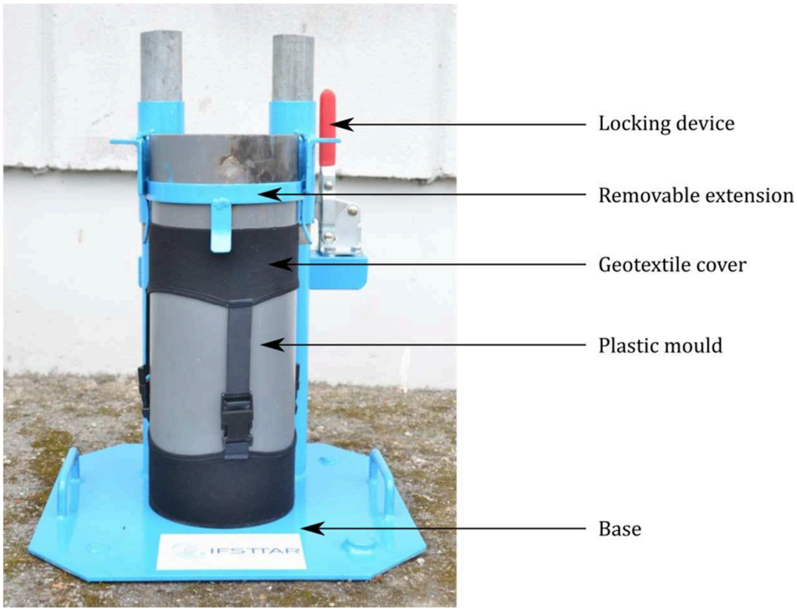


Figure 57. Device for cob specimen production.

Comparative study of the mechanical performance obtained with different test protocols were carried out with regard to the cob wall elements behaviour. The comparisons are focused on the shrinkage ratio, bulk density and pore size distribution obtained with 2 vegetal fibre lengths and 2 drying types.

4.4.3.2 Earth material source and geotechnical identification

The earth material employed for this campaign derives from an earthwork stock pile of the city of Saint Sulpice-la-Forêt (Brittany, France). This stock pile has been selected since this city possesses an important cob heritage and this earth has been employed with success by several skilled craftsmen for cob wall construction.

The identification of the material consisted in the determination of (1) particle size distribution, thanks to dry sieving for the coarse fraction (above 80 µm), according to French standard NF P 94-056 [288] and thanks to hydrometer method for the fine fraction (below 80 µm), according to French standard NF P 94-057 [289]; (2) methylene blue absorption capacity value according to French standard NF P 94-068 [290]; (3) plastic limit, liquid limit and plastic index according to French standard NF P 94-051 [353]; (4)

normal Proctor water content according to French standard, provided for information only, since the implementation of cob is carried out at plastic state [354]; (5) specific gravity according to French standard NF P 94-054 [355]. Water contents were determined at 105°C, according to French standard NF P 94-050 [356]. Soil classification was stated according to ASTM standard [357]. Results of material identification are presented in Table 19.

Table 19. Identification of the earth of Saint Sulpice-la-Forêt (Brittany, France) employed for the specimen production.

Clay (0 - 2 µm) (%)	**Silt (2 - 50 µm) (%)**	**Sand (50 µm - 2 mm) (%)**	**Gravel (> 2 mm) (%)**	**Methylen Blue Value (g/100g)**
3	18	42	37	1.01
W_P (%)	**I_P**	**W_{OPN} (%)**	**γ_{OPN} (g.cm^{-3})**	**Soil classification (ASTM)**
29.1	15.7	20.1	1.67	Clayey sand (SC)

4.4.3.3 Specimens production

Cob was mixed by foot treading, according to the vernacular cob process of Brittany (case (a) section 3.3.3.1), with a fibre content of 0.9 % by mass, at a plastic consistency.

Four fibred cob wall elements (600 mm long, 600 mm high and 300 mm thick) were manufactured according to the vernacular cob process of Brittany (case (a) section 3.3.3.1). Average fibre length was 150 mm. Walls were let dry under natural conditions inside a laboratory for 6 months prior testing.

Three criteria were studied in order to propose a laboratory procedure of production of cob specimen: the mould type, the fibre length and the drying conditions. Indeed, the side wall effect of the mould is deemed to have a strong influence on specimen's quality. Two different moulds are tested, one with strong side wall effect (cardboard cylinders designed for concrete) and cylinder with inner face covered with a low stiffness flexible geotextile (Figure 57). Long fibres (50 cm) cannot fit inside cob mould and had to be cut. Two different sizes were used to evaluate the effect of fibre length. Finally, on-site drying conditions (air-drying) and laboratory drying conditions (oven dried at 40°C) are compared in order to assess drying effect of cob specimens. Four different cob specimens' protocols were defined, and named according to these criteria, as shown in Table 20. For each protocol, four specimens were produced.

Table 20. Nomenclature of studied protocols.

Mould		***Fibre length***		***Drying***		***Protocol***
Cardboard (160 × 320 mm)	Plastic with Sock (150 × 300 mm)	Diameter (150 mm)	Radius (75 mm)	Oven (40°C)	Air (15 - 30°C)	
C	S	D	R	O	A	
■		■			■	***CDA***
	■		■	■		***SRO***
	■	■			■	***SDA***
	■	■		■		***SDO***
not concerned		■			■	***Wall***

Two different cylindrical mould types, with a 2:1 slenderness ratio [115,120] were employed: cardboard moulds designed for concrete (160 mm diameter, 320 mm height) and plastic moulds (150 mm diameter, 300 mm height) with inner face covered with a flexible geotextile (Figure 57). Specimens were made in 8 layers and compacted according to the normal Proctor protocol. Compaction is made at plastic state so that it is not possible to reach the optimum dry density. The normal Proctor compaction protocol is used for placing purpose only and, actually, compaction have little influence on dry density at plastic state [354].

Fibre length for wall elements and specimens CDA, SDA and SDO (Table 20) is set to 150 mm. In order to evaluate fibre length effect, a second fibre size was employed for SRA cob specimen (Table 20), with a size equal to the radius of the specimen, i.e. 75 mm.

Drying of cob walls and CDA and SDA specimens (Table 20) was conducted under natural conditions, i.e. air dried. In order to assess drying effect, SRO and SDO (Table 20) specimens were oven-dried at 40°C. After drying, oven-dried specimens were conditioned in a temperature controlled laboratory, set to 20°C, for 2 weeks prior to mechanical tests.

4.4.3.4 Mechanical and microstructural characterization of specimens

After drying, specimens were weighed and their volumetric changes were measured thanks to a vernier calliper. Bulk densities and average vertical and horizontal shrinkages were calculated. In order to compare specimens of different sizes, the vertical shrinkage is divided by the horizontal shrinkage (V/H) and this criterion is reported. Pore size distributions were determined thanks to Mercury Intrusion Porosimetry (MIP). MIP is a powerful laboratory technique to investigate the effect of compaction and shrinkage on microstructural properties of earth materials [358].

Uniaxial Compressive Strength (UCS) tests were controlled in displacement at a speed of 1 $mm.min^{-1}$ [115]. Tests for cylindrical specimens were carried out on an electromechanical press, with a 100 kN load cell. Tests for wall elements were conducted on a hydraulic press with a 2500 kN load cell. UCS was defined as the maximum strength of the specimen.

Young's moduli were determined by 3 cyclic loadings and deformations measured in the central third of specimens, thanks to extensometers adjusted for cylindrical specimens and thanks to digital image analysis for the wall elements (Figure 58). Maximum stresses of cyclic loads were inferior to the third of the maximum strength so that Young's moduli were determined in the elastic domain. For each cyclic load the secant moduli was calculated. The average secant moduli are reported.

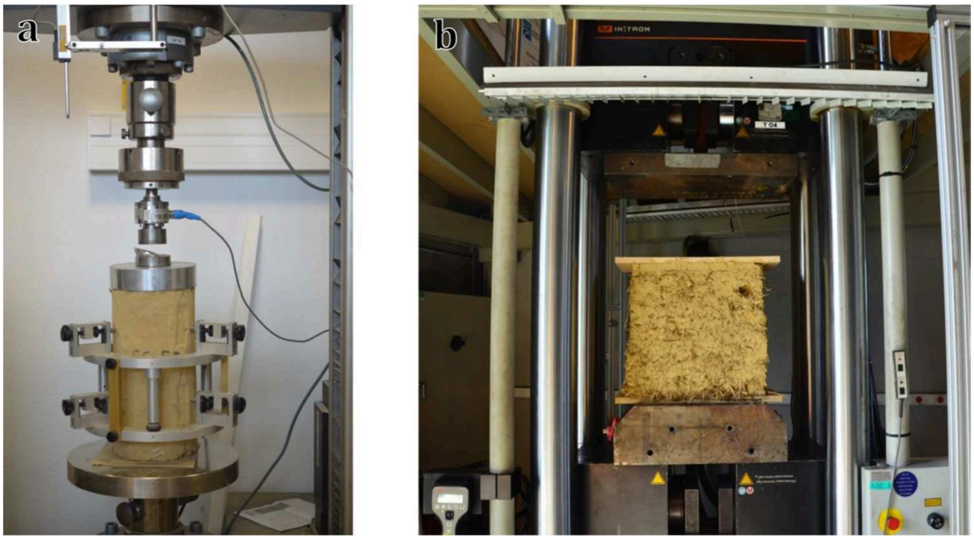


Figure 58. Mechanical tests of cob cylindrical specimens (a) and cob walls (b).

4.4.4 Results and discussion

4.4.4.1 Implementation influence on specimens' quality

As specimens shrunk during drying, then, specimens made with plastic moulds covered with a flexible geotextile (SRO, SDA and SDO) can be removed from plastic moulds and flexible geotextile cover after a 24 h drying period only. Specimens surface state is smoothed (Figure 59b). Because of shrinkage, the upper faces of these specimens were irregular and had to be cut, thanks to a block saw, in order to provide a flat bearing surface for mechanical tests.

Specimens made in concrete cardboard cylinder (CDA) stuck to the face of the moulds so that their surface state was of poor quality (Figure 59a). Moreover, concrete moulds are impervious and the bottom of specimens cannot dry, creating a high water content contrast between the dry upper face and the wet lower face of specimens. These specimens were therefore very difficult to remove from moulds. Another consequence of water stagnation is the rust growth at the bottom of moulds that sticks to the lower face of specimens and caused a poor quality surface state.

Compared to plastic moulds with flexible geotextile cover (Figure 57), concrete cylinder cardboard moulds are a simpler device, but they are not adapted to cob drying and produced cob specimens of poor quality. Nonetheless, the discussion on the selection of a protocol has to be based on the physical representativeness of the cob specimens with regard to the wall elements.

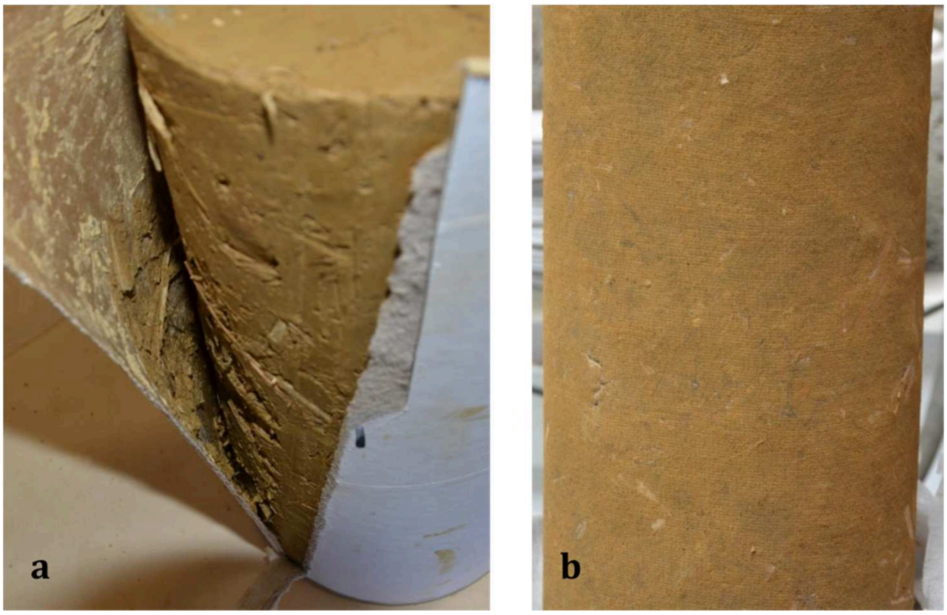


Figure 59. Surface state of specimens made in concrete mould (a) and in plastic mould with a flexible geotextile cover (b).

4.4.4.2 Comparison of shrinkage ratio

For cob, the dry density of the material is the result of shrinkage drying (section 1.4.1). The mechanical behaviour of cob depends on the density and therefore on the shrinkage rate. Vertical divided by horizontal shrinkage (V/H) is around 2 for wall elements, around 1.7 for SRO, around 1 for SDA and SDO and less than 1, with a large scattering, for CDA specimens (Figure 60).

The stress state of the wall elements during drying is only governed by dead load. Under this condition, vertical shrinkage is higher than horizontal shrinkage. The mass of the cylinder specimens is about 40 times less than these of the wall elements. The effect of dead load is thus less pronounced in cylinder specimens and their V/H shrinkage values are therefore lowers (Figure 60).

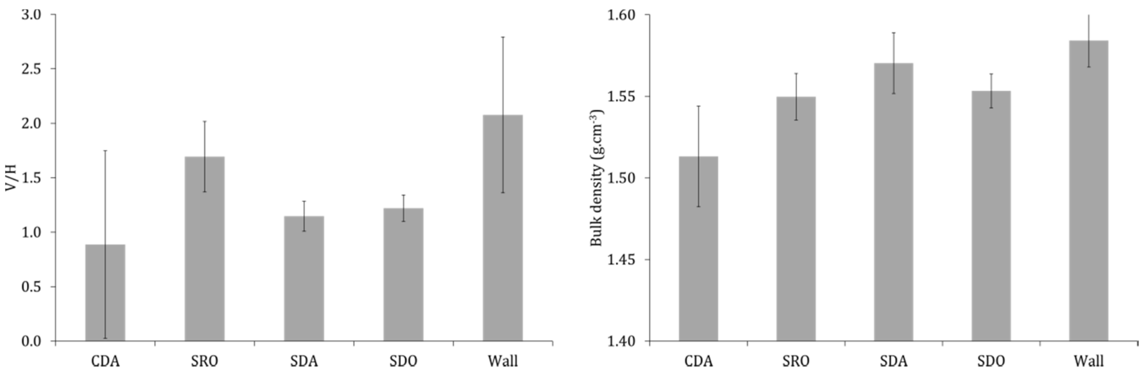


Figure 60. Comparison of average ratio of vertical by horizontal shrinkage (V/H), on left, and average bulk density, on right.

The large scattering of V/H results of CDA specimens highlights the operator dependency and the difficulty to make cob specimens of satisfactory repeatability with this protocol (Figure 60).

Specimens with fibre length equal to the specimen radius (radius-length fibres) (SRO) have a higher V/H shrinkage ratio than those made with diameter-length fibres (SDA, SDO) (Figure 60). Diameter-length fibres do not easily fit inside moulds and have a higher tortuosity than radius-length fibres. Hence, radius-length fibres are mainly horizontally oriented whereas diameter-length fibres have a more random distribution. Horizontal shrinkage is thus more restrained in specimens with radius-length fibres (SRO) than in those with diameter-length fibres (SDA, SDO). In the wall elements, fibres are mainly horizontally oriented, reinforcing the contrast between horizontal and vertical shrinkage.

4.4.4.3 Comparison of Bulk densities

Bulk densities of CDA specimens are lower than these of wall elements and exhibit a large scattering (Figure 60). Once again, the large scattering of CDA specimens highlights the operator dependency and poor repeatability of this protocol.

Bulk densities of SRO, SDA and SDO specimens do not exhibit significant differences (Figure 60). The SRO-SDA-SDO average bulk density is 1.56±0.02 $g.cm^{-3}$. Compared to the bulk density of wall elements, 1.58±0.02 $g.cm^{-3}$, apart from CDA specimens, all bulk density results are in good agreement. This confirms the representativeness of normal Proctor compaction protocol for placing of cob mixture in the specimen's moulds.

4.4.4.4 Influence of implementation in the microstructure of specimens

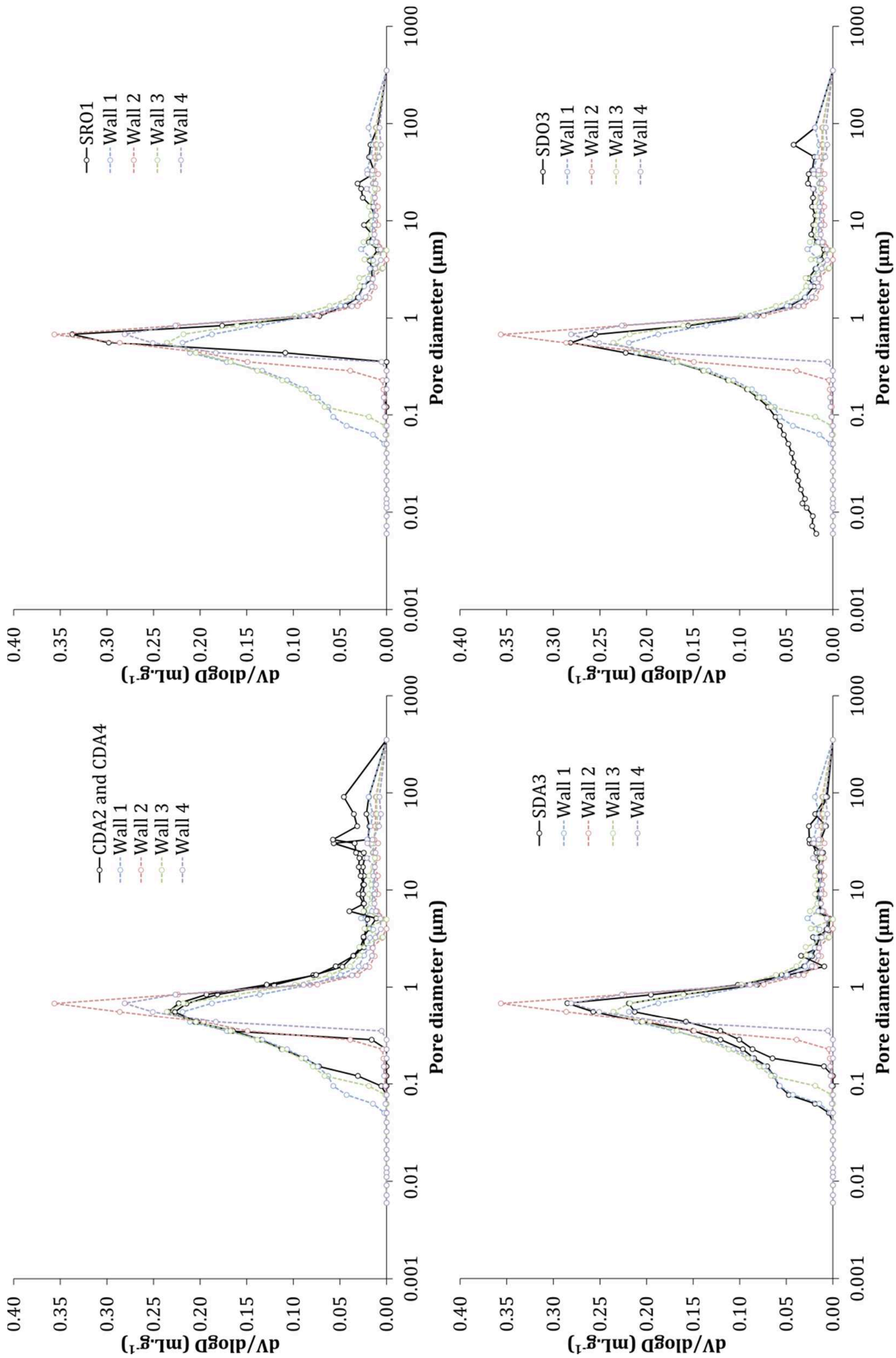


Figure 61. Comparison of pore size distribution obtained by mercury intrusion porosimetry.

Pore size distribution of all specimens exhibits a similar 1 μm pic (Figure 61). These results underline the homogeneity of cob mixture used for specimens' production. Nevertheless, the higher pore size named mesoporosity (10-100 μm) of CDA specimens (Figure 61) highlights the presence of cracks and a less effective compaction. This can be attributed to the adherence between the soil and the wall of the concrete cylinder cardboard moulds. This phenomenon is less significant with plastic cylinder moulds covered by flexible geotextile, thanks to the flexibility of the geotextile, following cob material strain under compaction. Mesoporosity of these specimens is therefore in good agreement with wall elements (Figure 61).

[358] studied the microstructural properties of hypercompacted earth blocks using Mercury Intrusion Porosimetry and author calculated inter and intra aggregate pore volume of specimens. Their results are compared with SDO3 in Figure 62. The material employed by [358] is different from the material employed in this study. Comparison thus provides only a general trend. Nevertheless inter ant intra aggregate pore volume are clearly higher in the cob specimen. The microporosity results from material humidification [359,360] and, in the present study, is less affected by compaction.

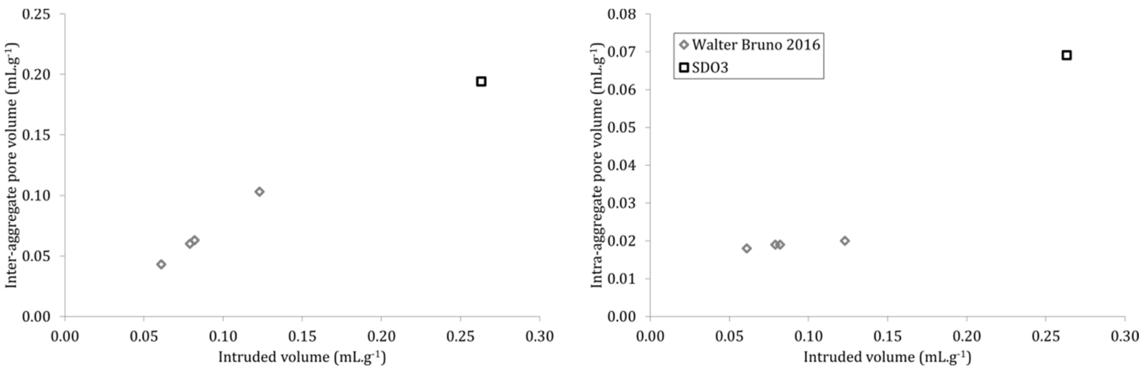


Figure 62. Comparison of inter and intra aggregate pore volume of hypercompacted earth blocks [358]*with SDO3*

4.4.4.5 Comparison of compressive strength and Young Modulus of cob specimens

Orders of magnitude of Uniaxial Compressive Strength (UCS) and Young's modulus (E) of cob wall elements (Figure 63) are in agreement with [15,22,115,120,351] but two times lower than these of [267]. Stress-strain curves of cob wall elements (Figure 64) are in agreement with the 3 stages described by [252]: (1) initial compaction, (2) linear stress/strain response and (3) initiation and propagation of cracks (section 4.4.2.1). Results of cob wall-elements mechanical tests are thus in good agreement with bibliography.

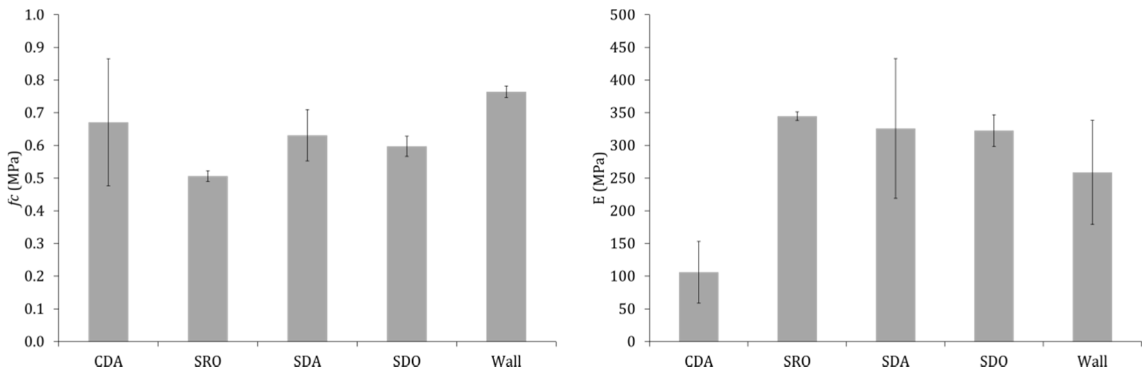


Figure 63. Comparison of average compressive strength (f_c, on left) and average Young's moduli (E, on right) for the four cob specimen protocols and cob walls.

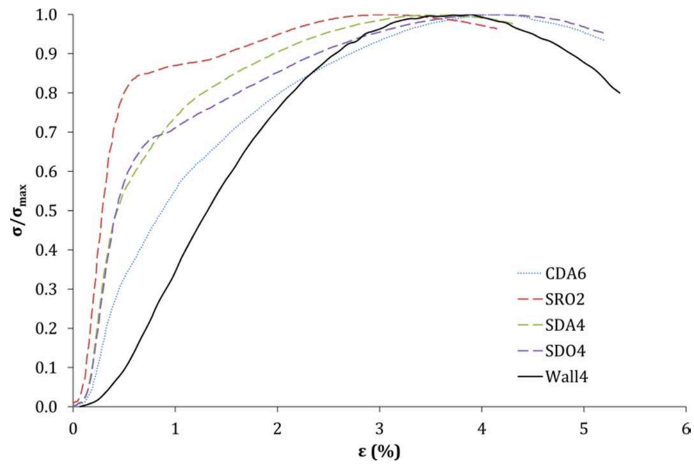


Figure 64. Normalized stress (σ/σ_{max}) strain (ε) curve of one specimen of the four cob protocols and cob walls.

Young's moduli of CDA specimens are very low compared to the Young's moduli of wall elements (Figure 63 and Figure 65). Indeed, the behaviour of CDA specimens is elasto-plastic and no elastic domain can be identified (Figure 64, Figure 66). Moreover, CDA results are outside the trends drawn for all other specimens (Figure 65). Hence, mechanical behaviour of CDA specimens cannot be regarded as representative of cob wall elements. This difference is attributed to the side wall effect of concrete moulds, reducing the bulk density of CDA specimens (Figure 60).

Average UCSs of cob specimens carried out according to the new laboratory procedure are lower than those of cob wall elements (Figure 63). This difference is attributed to a different compaction mode: wall elements were self-compacted under dead-load whereas cob specimens were compacted according to Proctor testing protocol. However, a trend can be drawn between bulk density and UCS, the higher the density, the higher the UCS (Figure 65). This tendency can be used to estimate the UCS of a cob wall, of known bulk density, thanks to cob test specimens realized during wall construction and tested according to the proposed laboratory procedure.

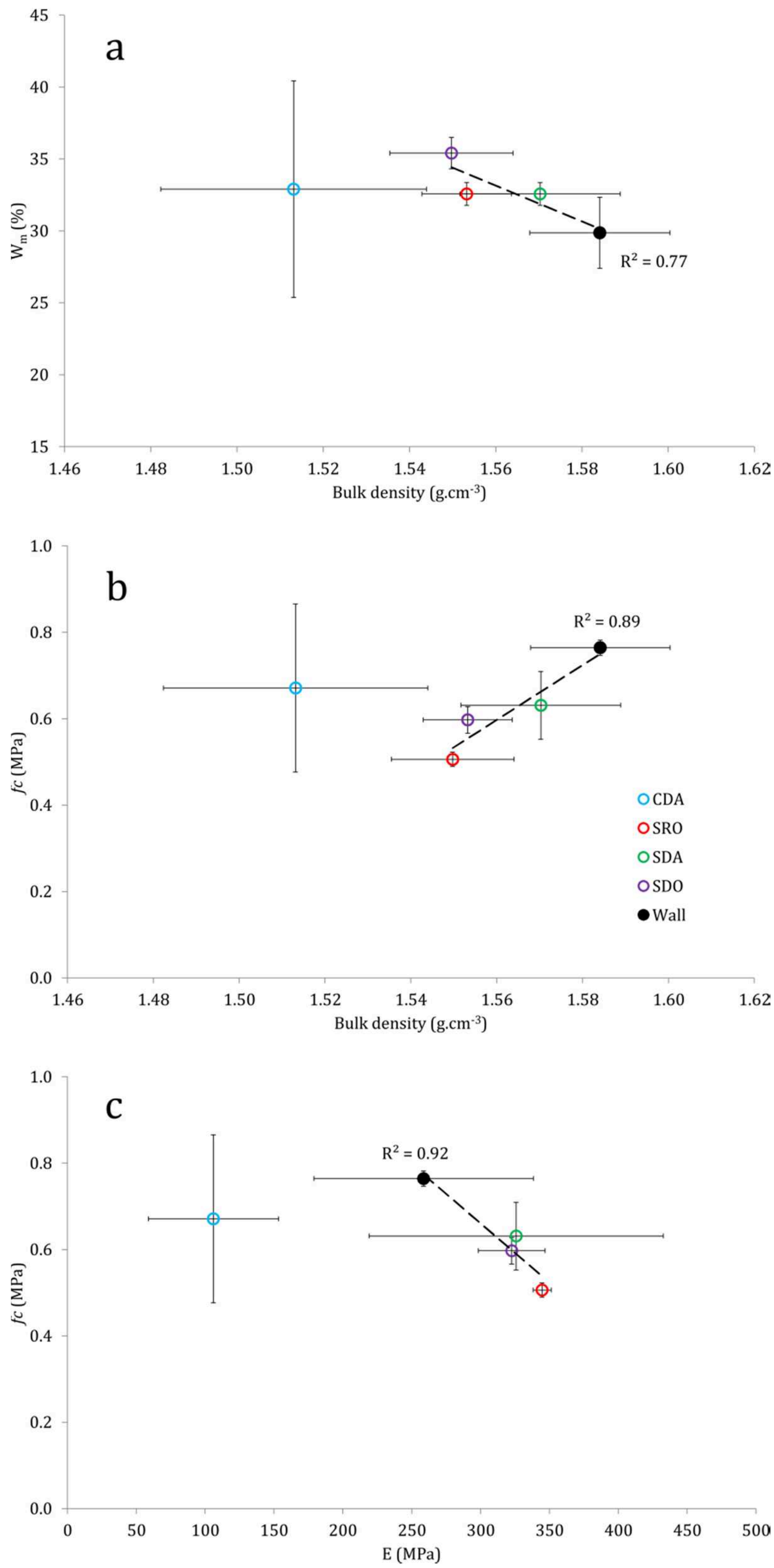


Figure 65. Average water content of manufacturing sae (W_m) with respect to average bulk density (a), average compressive strength (f_c) with respect to bulk density (b) and average Young's modulus (E) with respect to average compressive strength (f_c) of cob protocols (c).

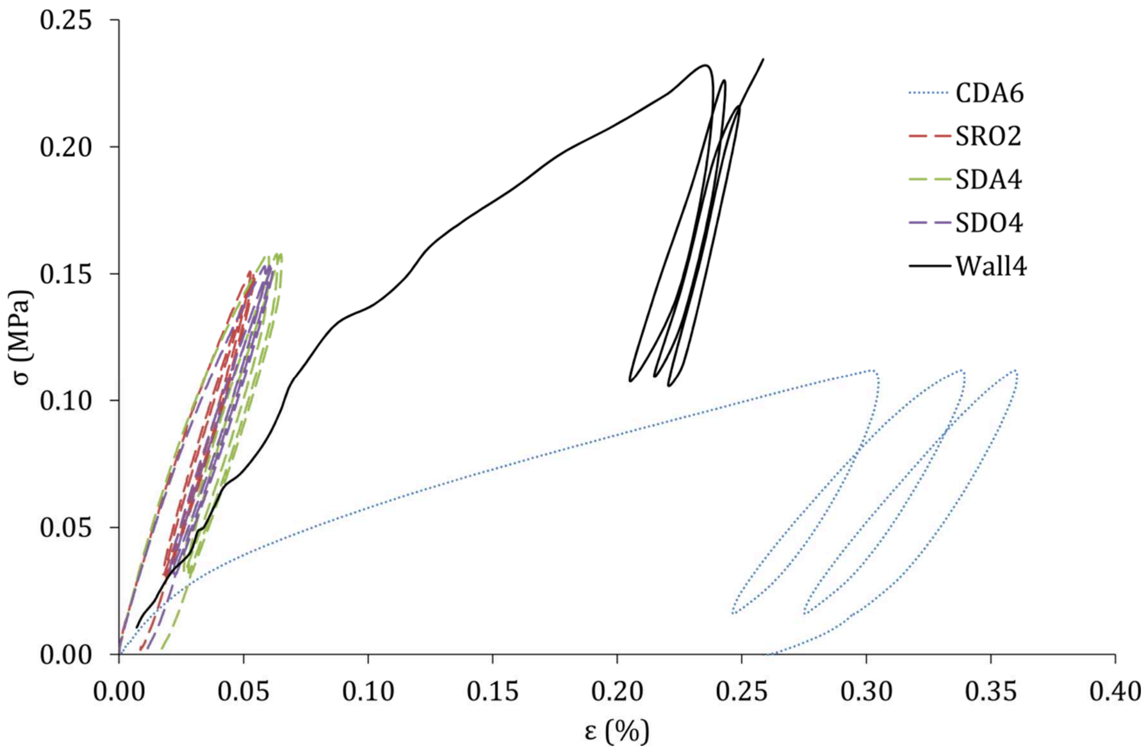


Figure 66. Cyclic loadings performed for modulus assessment

Another linear correlation can be drawn between Young's modulus and UCS of all specimens, except for CDA, indicating that the higher the stiffness, the lower the mechanical resistance (Figure 65). This tendency is in contradiction with the results of [349] obtained with rammed earth specimens and [361] obtained with pressed adobe bocks specimens, who found a positive strength-to-stiffness ratio. The negative strength-to-stiffness ratio of cob can be attributed to a more brittle (high Young's modulus) or a more ductile (low Young's modulus) mechanical behaviour of cob. For the more ductile behaviour, thanks to fibres, cracks and failures were distributed to a more important volume of cob material which enhanced their ability to bear higher strains. This tendency can be used to estimate the Young's modulus of cob walls of known UCS.

4.4.4.6 Comparative study of testing devices

The CDA protocol (Table 20), using concrete cardboard cylinders, is easy to use, but presents several limitations: (1) the side wall effect is strong and compaction is not efficient enough (Figure 61); (2) concrete moulds are impervious, the drying is therefore not homogeneous and drying times are very long; (3) earth material stick to the inner face of the mould and generates a specimen surface state of poor quality (Figure 59); (4) the large scattering of CDA results highlights the operator dependency of this protocol (Figure 60 and Figure 63).

The new laboratory procedure proposed here (Figure 57) presents several advantages: (1) the flexibility of the geotextile cover reduces the side wall effect of the cylinder and reduces the adherence of earth to the inner face of the cylinder (Figure 61); (2) it provides specimens with a good surface state (Figure 59); (3) thanks to horizontal shrinkage, specimens can be unmoulded after a 24 h drying only.

4.4.4.7 Influence of fibres length and orientation

Radius-length fibre specimens (SRO) have a fibre orientation and a Vertical/Horizontal (V/H) shrinkage ratio close to that of cob wall elements (Figure 60). However, the Uniaxial Compressive Strength, the Young's modulus and the stress-strain response of diameter-length fibre specimens is more representative of the mechanical behaviour of cob wall elements (Figure 64 and Figure 65). Fibre aspect ratio occurs to be a first order parameter with comparison to fibre orientation [362]. The use of fibre length close to that of the cob wall is then recommended.

Two modes of fibre length were identified for vernacular cob (section 3.3.2.3): small fibres (10-20 cm), and long fibres (40-60 cm). The diameter-length fibres specimens have the same fibre length that cob with short fibres. In the case of cob with long fibres, fibres are too long to fit inside the cob specimen and might be cut.

4.4.4.8 Influence of drying method

Drying conditions affect specimen shrinkage and have therefore an impact on mechanical behaviour. No significant difference occurs between air-dried (SDA) and oven-dried (SDO) cob specimens, for specimen's characteristics (Figure 60 and Figure 61) and mechanical behaviours (Figure 63, Figure 64 and Figure 65). The accelerated oven-drying can be regarded as representative of on-site drying conditions.

4.4.5 Cob laboratory testing procedure - Synthesis

The results of this preliminary study demonstrate that the protocol using concrete cardboard cylinders is deemed unsatisfactory for cob specimen production. In contrast, the new laboratory procedure proposed here, using plastic cylinders with inner face covered with a flexible geotextile produces cob specimens with bulk density and pore size distribution similar to that of wall elements. The new laboratory procedure succeeds in reproducing the irregular kneading effect of cob. Moreover, it allows estimating Uniaxial Compressive Strength and Young's modulus of a cob wall of known bulk density. This new laboratory procedure offers the advantage to be used either on-site, under air-drying and weather conditions, or in the laboratory, under oven-drying conditions. Nonetheless, more investigations are needed to validate this new laboratory procedure with other cob mixtures.

4.5 Synthesis of chapter 4

Earth construction will play an important role in the modern sustainable building of the 21st century if the actors of the sector adopt earth construction processes able to meet social demand, with low environmental impact and at an affordable cost. The study of earth heritage demonstrated the ability of historical earth builders to innovate in order to comply with social demand variations and technical developments. Earth construction benefits of an old and rich past and it would be a non-sense to leave this past behind. The analysis of earth heritage and the rediscovering of vernacular construction techniques is a valuable source of inspiration for modern earth construction. The valorisation of vernacular knowledge will save time, energy and avoid repeating past mistakes. The future of earth construction should be a continuation of past vernacular earth construction.

In Western countries, the environmental impact of construction was not a specific concern for past builders but it was part of their life. They were dependant on local environment. Any unsustainable building practice would have had a direct consequence on their living conditions. They developed common-sense rules to avoid such practices. Moreover, economic and environmental costs were correlated: it was expensive to spend energy. Since the exploitation of fossil energies, this correlation no longer exists. Conventional building materials expanded due to this low-cost energy context. Current tensions on the energy market increase the need to propose sober construction processes. The use of local and unprocessed earth is a way to meet sober construction process needs.

Many skilled craftsmen possess the required experience to build with these low impact processes, but the building sector regulation is not adapted to the use of local, natural and variable materials. This regulation constraint led several authors and producers to propose to standardise earth materials: by granular correction and admixture addition or by exploitation of earth quarries. However, these solutions alter the beneficial impact of earth buildings. Since the use of earth, with regard to conventional material, is legitimated by its low impact, these solutions are deemed as irrelevant for earth construction sector in a long term perspective.

Another solution deemed more relevant for earth construction sector, is the elaboration of performance based procedures. Regardless of the material, the formulation and the implementation technique, the real performance of building element is assessed. Thus, performance based approach allows using any kind of earth and process, and more specifically local raw earth implemented with low-embodied energy construction technique. It also avoids standardisation of the construction process and contributes to the preservation of the diversity of local construction cultures. In this chapter, a performance test procedure for earth plasters and a laboratory testing procedure, which can be used as a basis for a future performance based procedure, is proposed for cob. The plaster performance test procedure, proposed in 2012, is part of the French code of practice for earthen wall plastering. This code of practice has been validated by the French inter-professional insurance authorities and is routinely used by earth masons. It is also applied by several laboratories for research purpose. This procedure set a precedent to promote the use of performance based approach in earth construction.

Chapter 5 General conclusion

The building sector is responsible for high natural resource and energy consumption which leads to greenhouse gas emissions that contribute to global warming. These resource and energy consumptions are not sustainable in a long term perspective. There is thus a need to significantly reduce the environmental impact of the building sector. The use of local, natural and unprocessed materials offers promising low impact building solutions (section 1.1). Their wide spatial variability is, however, an obstacle for a large-scale use. The use of locally sourced and unprocessed materials requires a specific approach adapted to their variability.

The construction strategies developed by past builders were dictated by the local climate and the quality and the amount of locally available construction materials. These construction strategies can be regarded as an optimized management of local, natural and variable resources and are a source of inspiration for modern sustainable building. Unfortunately, this knowledge was almost lost in Western countries during the 20th century. Earth building heritage is a unique testimony of these low impact construction strategies. Vernacular earth construction know-how rediscovering requires the development of rational heritage investigation means. Another issue regarding the use of natural and variable building material is their compliance with modern building regulation. The development of performance based testing procedures is proposed as a solution to facilitate the use of earth as a building material.

In this manuscript, two different methods were employed to identify vernacular material sources for earth construction. The first method combined micromorphological analysis of samples collected in earth heritage building with pedological survey. The second method identified soils suitable for earth construction at regional scale using cross-referencing of heritage and soil databases. The construction processes were described thanks to a bibliographical analysis for cob, and thanks to a micromorphological analysis for a cob barn and a rammed earth farm. Finally, two different performance based testing procedures were proposed, one for earth plasters and the second one for cob walls. Key results of this work are summarized below.

Micromorphological and pedological analysis permit the identification of the material source of a rammed earth farm (section 2.3). It is located 1 km away from the site. The construction is dated 1860. The network and mean of transportation of this time enable us to envisage the carriage of the earth over such a distance. Indeed, the transportation of the 12 m^3 of earth required for wall construction corresponds to 6 tumbrel travels. The excavated horizon is just below the humiferous horizon and principally concerns the Eg soil horizon present between -5 to -35 cm depth. Considering a 30 cm thickness of soil, the surface excavated to build the wall is estimated to 40 m^2. The same calculation performed for the entire building gives an excavated area of approximately 800 m^2. The selection of a particular horizon, located 1 km away, requiring excavation of soil on such a large surface area, tells us how carefully the choice and the excavation of earth for construction was made by the 19th-century craftsmen and highlights their sophisticated know-how. This result confirms the relevance of the vernacular earth construction rediscovering process.

Cross-referencing of spatialized pedological and heritage data enabled identifying the regional resource of earth suitable for cob construction in Brittany (France) (section 2.4). Six different earth texture and Cation Exchange Capacity (CEC) classes were identified. Among soils of Brittany, the most suitable earths are the siltiest. This result is in contradiction with recommendations available in the literature, suggesting the use of sandy-clayey soils. The current earth suitability recommendations are based on too restrictive results or on theoretical laboratory approaches, whereas vernacular soil selection is the result of time-tested empirical experimentations. Textures identified in this study enlarge the possible sources of earth suitable for cob construction and call into question recommendations available in the literature. Results also highlighted an optimum clay content which decreases when CEC of clays increases. This relationship was suspected for a long time and was brought to light in this study for the first time. Using earth suitability results, geographical representations of Brittany cob resource availability were drawn by percentage of surface and by percentage of volume. The availability of cob soils, expressed by surface, is greater to the northeast part of Brittany and well correlated with the geographical distribution of cob heritage, whereas there is no correlation between the geographical distribution of cob soils by volume and cob heritage. This result suggests that the geographical continuity of the resource was more important than the volume of the resource in order to allow the development of a local earth construction culture.

Macroscale quantification of orders of magnitude of the volume of available soil resource for cob in Brittany were calculated. The volume of soil available was estimated at 6.8 billion m^3, i.e. 8.8 billion tonnes, and represents 23% of total soils of Brittany. The estimated proportion of the resource already consumed by past builders is 0.03%. The hypothetical consumption of the entire resource would enable the construction of 88 million homes and if all housing of Brittany were made of cob, 2.1% of the resource would have been consumed. These estimations illustrate the huge availability of earth material in Brittany. These calculations take into consideration the best cob soils only. Considering that it is possible to use other types of earth with mechanized cob, that skilled craftsmen are able to use other soils and that other earth construction techniques could be employed, these scales of magnitude should, therefore, be regarded as minimum values in a modern earth construction context. Nonetheless, the soil is a non-renewable material on the human time scale and it provides various ecosystem services like provisioning, regulating, cultural and supporting services. Excavation of earth for construction might impact multifunctional roles of soil. Management of the consumption of this resource should, therefore, be carefully considered. Currently, earthworks excavations generate large amounts of landfilled soils. In Brittany, 2.8 million tonnes of soils are landfilled every year. Considering that 23% of these landfilled soils are suitable for cob, in 2012, 0.6 million tonnes of earth were available and would have enabled the construction of 52% of the individual housing of Brittany that year. The resource of earth suitable for cob in Brittany is huge and earthwork excavations already provide large amounts of earth every year. This high-quality construction material could be valued in the building sector, instead of ending up as waste in landfills.

A cob bibliographical analysis (section 3.3) provided a detailed description of vernacular cob construction process and a classification of cob variations in 4 cases (section 3.3.3.1). Slenderness ratio of lifts was proposed as an indicator of the convenience of earth and of associated process variation, the higher the slenderness and the better the convenience. This bibliographical analysis illustrated the diversity of strategies employed by past cob masons to deal with cob construction process constraints. It was estimated that, at least, hundreds of variations existed for this process. This diversity is a key to promote the use of locally available and unprocessed construction materials, as it broadens the range of sustainable construction solutions and therefore the possibility to find a sustainable construction process adapted to a local context.

For the first time, micromorphological analyses were performed on specimens collected in rammed earth (section 3.4) and cob (section 3.5) heritage walls. Pedofeatures related to material implementation provides information on the water content of manufacturing stage, the blending, kneading and compaction degree, potential admixtures and size and shape of layers/clods. All these elements permitted to propose an accurate description of the construction technique employed by past builders. For the rammed earth and the cob building studied here, we succeeded rediscovering the construction process employed by past craftsmen. A comparison of micromorphological features related to the rammed earth farm and the cob barn at different process stages was drawn.

The maintenance of earth heritage buildings and the consideration of earth construction technique in modern building require a rational approach complying with building regulation. To allow using local earth, which present high variation from place to place, performance based test were proposed, one for plasters and another one for cob.

A performance based on-site procedure was proposed for earth plasters (section 4.3). A shrinkage test, followed by a shear test validates plaster formulations. The shrinkage test eliminates formulations beyond a shrinkage threshold specific to the plaster-wall combination and enables to find the best plaster formulation. Then the shear test validates this formulation if it offers sufficient adherence and thus sufficient shear strength to the plaster-wall interface. Earth plasters exhibit an optimum shear strength that depends on clay content. An increase in the amount of clay reinforces the plaster until the effect of shrinkage becomes predominant and decreases the shear strength. This plaster performance test procedure was proposed in 2012 as part of the French code of practice for earthen wall plastering. This code of practice has been validated by the French inter-professional insurance authorities and is routinely used by earth masons. It was also applied with success by several laboratories for research purpose and several authors recommend this testing procedure since it is judged as representative of on-site conditions. Some authors, however, recommended increasing the size of shear test specimens. This procedure set a precedent to promote the use of performance based approach in earth construction.

An innovative laboratory procedure for cob sample production was proposed and tested in order to assess the mechanical performance of cob walls (section 4.4). A flexible geotextile cover is placed on the inner face of a cylinder mould wall (diameter 150 mm, height 300 mm) to reduce the friction and the adherence with soil. Specimens carried out according to the new testing procedure are compared to 600×600×300 mm cob wall elements. Average Uniaxial Compressive Strengths (UCS) of cob specimens made according to the new laboratory procedure are lower than those of cob wall elements. This dissimilarity is attributed to a different compaction mode: wall elements were self-compacted under dead-load whereas cob specimens were compacted according to Proctor testing protocol. However, a trend can be drawn between bulk density and UCS: the higher the density, the higher the UCS. This tendency can be used to estimate the UCS of a cob wall, of known bulk density, thanks to cob test specimens realized during wall construction and tested according to the proposed laboratory procedure. Linear correlation can be drawn between Young's modulus and Uniaxial Compressive Strength of all specimens indicating that the higher the stiffness, the lower the mechanical resistance. Although this result is in contradiction with findings for rammed earth and pressed adobe blocks, this trend can be attributed to a more brittle (high Young's modulus) or a more ductile (low Young's modulus) mechanical behaviour of cob. For the more ductile behaviour, thanks to fibres, cracks and failures were distributed to a more important volume of cob material which enhanced their ability to bear higher strains. This tendency can be used to estimate the Young's modulus of cob walls of known UCS. The proposed laboratory procedure provides basis for the development of a performance based test for cob.

The multidisciplinary approach proposed in this work combined micromorphology, pedology, geotechnics and cultural heritage disciplines. It provided complementary tools to assess pedological sources of construction material and geotechnical characteristics of earth employed in vernacular earth heritage. It also provided a detailed description of the construction process of vernacular earth heritage.

The results of this work offer several research perspectives. From an architectural and a historical point of view, this knowledge would enable to follow the evolution and the spread of earth construction processes. From a technical point of view, it would allow us to rediscover the solutions employed by past builders to overcome obstacles that are still relevant nowadays: influence of soil, geography, geology and climate on construction process choices. Some improvements can be proposed for this methodology. This more specifically concerns the determination of water content of manufacturing stage, which has a great impact on kneading/compacting action. Only the material state, i.e. solid, plastic or liquid, can be determined presently. A correlation could possibly be found between porosity shapes or porosity distribution and the water content of manufacturing stage. Another outlook for future could be the utilisation of image analysis to go from a phenomenological approach to a physical approach. However, pedofeatures are complex and multiscale objects and their study requires a high expertise. The development of such image analysis tools would necessitate a significant effort.

Suitable soils for construction are often described as “clayey soils” and recommended textures proposed in the literature are most of the time sandy-clayey soils. However, results suggest that past builders might have preferred silty soils. Further investigations are needed to highlight the reasons for these differences. To further the discussion on the identification and quantification of soils for construction, the same methodologies should be applied to other regions with different earth construction techniques and climates.

Earth construction will play an important role in the modern sustainable building of the 21st century if the actors of the sector adopt earth construction processes able to meet social demand, with low environmental impact and at an affordable cost. The study of earth heritage demonstrated the ability of historical earth builders to innovate in order to comply with social demand variations and technical developments. Earth construction benefits of an old and rich past and it would be a non-sense to leave this past behind. The analysis of earth heritage and the rediscovering of vernacular construction techniques is a valuable source of inspiration for modern earth construction. The valorisation of vernacular knowledge will save time, energy and avoid repeating past mistakes. The future of earth construction should be a continuation of past vernacular earth construction.

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Appendices

Appendix A Definitions of soil, geomorphology and geology terms

Soil (Pedological definition): product of the weathering of rocks by geological, topographical, climatic, physical, chemical and biological factors [113].

Soil (Geotechnical definition): cohesionless materials overlying the solid bedrock crust [89,95].

Topsoil: first horizon of a soil, where organic matter accumulate (A, O) [94,114,287].

Subsoil: horizons located below topsoil [94].

Alterite (or weathered bedrock, weathered mantle): Levels located between unweathered bedrock and soil horizons [103].

Isalterite: Lower level of alterite, in which the original petrographic structure is maintained and still recognizable [103].

Alloterite: Upper level of alterite in which the original textural features have partly or totally disappeared [103].

Weathering profile: one-dimensional section of weathered mantle from its surface through all its zones to parent material [94,108]

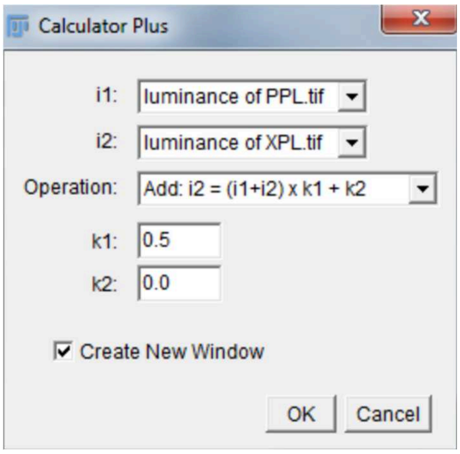
Regolith: unconsolidated mantle of weathered rock and soil material on the Earth's surface [104,108]

Pedolith: zone where the pedological processes have destroyed the original bedrock structure [106,108].

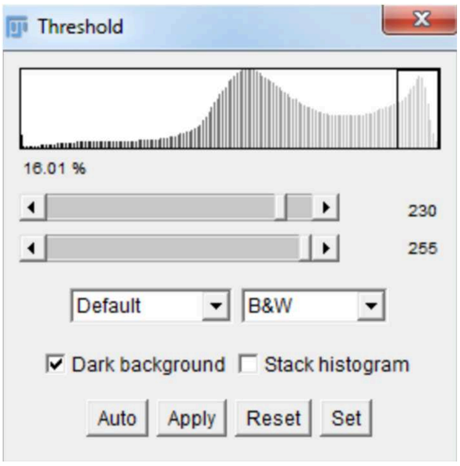
Saprolith: zone where the bedrock fabric is weathered but primary bedrock structures are recognised. The saprolith includes saprolite (containing more than 20% altered minerals) and the saprock (containing less than 20% altered minerals) [106,108].

Appendix B Image processing with Fiji

1. Open PPL and XPL image of thin section
2. Image/Color/RGB to Luminance
3. Image/Adjust/Brightness/Contrast
   Auto/Apply
4. For XPL image only: Edit/Invert
5. Save the treated images as, for example, "Luminance of PPL" and "Luminance of XPL"
6. Process/Calculator Plus
   i1: 'Luminance of PPL'
   i2: 'Luminance of XPL'
   Operation: Add
   k1: 0.5
   k2: 0.0
   Tick the box 'Create new window'



7. Save the 'Result' image and close 'Luminance of PPL' and 'Luminance of XPL'
8. Image/Adjust/Brightness/Contrast
   Auto/Apply
9. Set the scale of the 'Result' image: Analyse/Set scale
   Distance in pixels: 1
   Known distance: 5.3
   Pixel aspect ratio: 1.0
   Unit of length: µm
10. If necessary, rotate the 'Result' image: Image/Transform/Rotate
11. Crop the 'Result' image in order to get an image covering earth material only: draw a rectangle thanks to 'Rectangular' tool, then Image/Crop
12. Process/Filters/Median
    Radius: 3.0 pixels
13. Image/Adjust/Threshold
    Select 'Default' and Black and White mode ('B&W')
    Tick the box 'Dark background'
    Set minimum and maximum threshold values to 255
    Reduce the minimum threshold until voids are clearly visible, but before than quartz minerals are clearly visible. In the present case, min threshold was set to 230.
    Apply



14. Process/Morphology/Grey Morphology
    Radius of the structure element (pixel): 3.0
    Type of structure element: circle
    Operator: erode
15. Process/Morphology/Grey Morphology
    Radius of the structure element (pixel): 3.0
    Type of structure element: circle
    Operator: dilate
16. Process/Morphology/Grey Morphology
    Radius of the structure element (pixel): 3.0
    Type of structure element: circle
    Operator: close
17. Save the treated image
18. Analyse/Set Measurements
    Tick the box 'Area'
19. Analyse/Analyze Particles
    Size (pixel^2): 0-Infinity
    Circularity: 0.00-1.00
    Tick the box 'Display results'
20. Save the file 'Results.txt'

Appendix C List of publications

Hamard, E., Lemercier, B., Cazacliu, B., Razakamanantsoa, A., Morel, J-C., Earthwork waste reuse capacity for earth construction, ***under submission***.

Vinceslas, T., Hamard, E., Razakamanantsoa, A., Bendahmane, F., A new laboratory procedure to assess the mechanical performance of cob, Environmental Geotechnics, ***under publication***.

Hamard, E., Cammas, C., Fabbri, A., Razakamanantsoa, A., Cazacliu, B., Morel, J.-C., 2016. Historical Rammed Earth Process Description Thanks to Micromorphological Analysis. Int. J. Archit. Herit. 3058, 1–10. doi:10.1080/15583058.2016.1222462

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Appendix D List of communications

Hamard, E., Earthwork waste reuse capacity for earth construction, 2nd French-Brazilian Workshop on Construction and Demolition wastes recycling, Nantes, 16-18 October 2017.

Hamard, E., Morel, J.-C., Vernacular and modern earth construction: a continuity, Workshop Earthen empire: adoption and adaptation of soil-based building materials in the Roman vernacular, Edinburgh University, 22-23 September 2017.

Hamard, E., 2017, Construire en terre ?, Rencontre recherche-entreprise Novabuild, Saint Herblain, 4 mai 2017.

Hamard, E., 2017, Développement d'essais performantiels – Enduits sur support terre, Journée assurabilité des ouvrages en terre crue, Collectif Terreux Armoricain, École Normale Supérieure d'Architecture de Bretagne, Rennes, 27 janvier 2017.

Hamard, E., Lemercier, B., 2017, Des matériaux utiles à portée de main : le réemploi de la terre pour la construction, Forum des ressources de la région Bretagne, Pontivy, 20 janvier 2017.

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Dugelay, S., Hamard, E., Perrot, A., 2016, Terre Crue, disponibilité, usage, Rencontre professionnelle du bâtiment, Comment construire différemment ?, Université Bretagne Sud, Région Bretagne, Lorient, 4 octobre 2016

Hamard, E., Morel, J.-C., 2016, Performance tests to assess the coating of plasters on vernacular earthen walls, 2016 EMI International Conference, Engineering Mechanics Institute, ASCE, Metz, October 25-27 2016.

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