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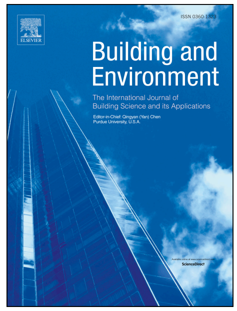

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Cob, a vernacular earth construction process in the context of modern sustainable building

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Abstract

The will of reducing environmental and social impact of building industry has led to a renewed interest in earth construction. Most of earth construction literature dealt with rammed earth or adobe techniques, but very little with cob. Yet, cob participates in the diversity of vernacular earth construction processes that value local materials and is an alternative to rammed earth and adobe in specific geographical conditions. Conservation of cob heritage also requires a better knowledge of this vernacular construction process. This bibliographical analysis gathered extensive data on cob process and summarized the different cob process variations, attempting to take into account their diversity. This analysis allowed us to provide novel data on cob process, and more specifically, (1) a clear definition of cob with regard to other earth construction processes, (2) a first summarized description of cob process that clearly distinguished its variations, (3) a list of fibres traditionally employed, (4) values and, if possible, average and standard deviation for fibre length, fibre content, manufacture water content, drying times, lift heights and wall thicknesses, (5) a summary of the strategies to manage shrinkage cracks, (6) a criterion on the quality of implementation and/or earth for cob, based on slenderness ration of lifts and (7) a discussion on the evolution of cob process with regard to societal evolutions.

Highlights

- A clear definition of cob is proposed.
- A first summarized description of cob process is proposed.
- First order of magnitude of characteristics of cob process is proposed.
- A summarization of the strategies of management of shrinkage is proposed.
- A criterion on the quality of implementation and/or earth for cob is proposed.

Key Words: cob; vernacular; earth construction; process; sustainable building.

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1 Introduction

Cob is part of vernacular earth construction techniques. It consists in stacking clods, made of a mix of plastic earth, in order to build a monolithic wall. As other earth construction techniques, cob encountered a renewed interest for its low environmental impact in comparison to conventional construction materials [1–4]. Indeed, the building sector is one of the largest consumer of natural resources [2,3,5–8]. It also generates large amounts of waste [5,6] and produces greenhouse gases that participate to climate change [6–10]. Embodied energy together with operating energy of the building sector represent approximately 40 % of global energy use [5,6,8,9].

Until 2000s, operating energy only was considered because of its dominant share in the total life cycle. Since, the use of more efficient equipment and insulations modified the balance between embodied energy and operating energy so that the proportion of embodied energy increased [6,8,11]. In order to pursue energy saving effort, the next challenge of the building sector will be the reduction of embodied energy [8]. This involves good maintenance of heritage and the use of construction materials with low embodied energy [12,13].

Improving durability of cob heritage will save as much energy as it would be required for new constructions [14]. Still existing cob building heritage is estimated to 50 000 in Germany [15], 40 000 in Devon (UK) [16,17], 30 000 in Ille-et-Vilaine (France) [18] and 20 000 in Manche (France) [19]. In European Union, cob heritage thus represent, at least, 200 000 buildings. Those buildings date back to the first half of 20th century, the 19th, 18th century and are even older [9,15,18,20–39], which prove their high durability (Figure 1). This longevity is only possible if properly maintained by skilled craftsmen [9,30,40–44]. Unfortunately, this expertise is lost in the Western countries [1,4,17,42,45–47] and inappropriate maintenance is a serious threat to cob heritage [16,41,44]. Hence, there is a need to describe and understand cob construction process in order to propose suitable maintenance solutions in order to increase buildings lifetime.

Former builders mainly had animal energy and unprocessed local materials for construction purpose. Centuries after centuries, they optimized the use of available natural resources, according to geographical context and societal evolutions, and developed local constructive cultures [1,42,48]. As a consequence, embodied energy of earth construction is very low in comparison to other materials conventionally used in construction [1,2,9,10,16,46,49–53]. For example, embodied energy of a wall made of earth is about 20 times less than that made of hollow cinder blocks [9,10]. Earth construction offer other benefits: better social impact [5], low greenhouse gas emissions [6,9,10,46,49,54], high thermal mass [1,19,30,49,52,55–63], good indoor air quality [1,7,9,10,49,51,54,64–67] and reversible clay binding allowing a complete and low-energy recycling [10,16,31,49,50,52–54]. As these local constructive cultures are a source of inspiration for anti-seismic constructions [48], they can be used to propose future energy-efficient building solutions. Earth building heritage is therefore a precious testimony of low-environmental impact construction.

The aim of this paper is to propose a clear definition of cob with regard to other earth construction techniques, analyse cob bibliographic data in order to provide a description of vernacular cob construction process and an explanation of the key factors of the process.

Among the 133 references used to describe local cob construction techniques, 77 % concerned France and United Kingdom (Table 1). This bibliography is an overlook to vernacular cob construction techniques around the world, with a focus on France and United Kingdom.

In this paper, soil names the material in its natural context and earth names the material extracted for construction purpose.

2 Cob definition

2.1 The place of cob in the family of earth construction techniques

To provide a definition of cob it is necessary to understand what makes this earth construction technique different from the other ones. Thus, before proposing a definition for cob, 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 [9,17,36,68–72]. Among those classifications, those based on the distinction between wet methods and dry/compaction methods [9,17,71] are judged more appropriate for classification purpose. For wet processes, earth mixture is placed at plastic state and mechanical strength of the material is provided through drying shrinkage densification (adobe, cob). For dry processes, earth mixture is placed at optimum Proctor 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, through masonry units (Compressed Earth Block and adobe) or direct monolithic wall realization (cob and rammed earth).

These classifications are adapted and supplemented with non-load bearing techniques (wattle and daub and plasters) and a classification is proposed in Figure 2. This classification is based on three criterions: (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 at manufacture water content in order to build a monolithic wall / infilling of a wooden structure / overlying of walls) and (3) structural role of the earth element (load-bearing and free-standing walls / non-load bearing walls).

Using this classification, it is possible to propose a definition for cob. This definition should be wide enough to comprise all process variations, but precise enough to differentiate cob process from other earth construction techniques. The following four key characteristics are proposed to define cob process: (1) realization of earth elements in a plastic state, (2) implemented wet, in order to build a (3) monolithic and (4) load bearing or freestanding wall.

2.2 Cob name

A large variety of vernacular names for earth construction techniques (Table 2) 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 cause equivalence problems.

Indeed, those names sometimes describe similar techniques and sometimes describe different variations of cob process. As an example, *bauge* in Brittany (France) and *mâsse* in Normandy (France) describe the same technique (see case a, section 3.3.1), as well as *caillibotis* in Brittany and *gazon* in Normandy also describe the same technique (see case b, section 3.3.1). The term *bauge* has imposed on the entire francophone area instead of regional terms to name this technique [73]. But the word *bauge*, in its strict meaning, refers to the earth, fibre and water mixture that was traditionally employed in Brittany for earth construction [26,74–77]. Although this term refers to the mixture obtained, it necessarily 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.

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 [4]. Some authors [36,68,69] proposed to name this technique “piled earth”, since it better described this construction process. Nevertheless, it failed, for the moment, to impose instead of the term cob. As for *bauge*, it should be specified when cob is used in a strict sense (cob s.s., the vernacular technique used by former builders in Devon [16]) to differentiate it from its acceptance as a general term, cob.

3 Cob process

A summary of cob construction process is proposed in Figure 3, 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.

3.1 Material supply

3.1.1 Earth

Earth source selection

For former builders, the first step of the cob building process was the identification of earth material source. Thanks to the legacy of previous builders and their own experience, they had a specific knowledge of the way to choose earth for cob construction [9,22,78]. 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 [78,79]. This knowledge is nowadays lost in the West, but it is possible to try to rediscover and translate it by mean of geotechnical analysis. Some authors have characterized earth materials collected inside or next to old cob walls [44,52,80–87]. Results are too small and incomplete to summarize them. However, vernacular cob earth textures were defined in the literature as loam [15,20,21], clay [22,31–34,88–94], silt [31,82,93,95] or clayey-silt [31,35,93,96] soils. Silts, sands and gravels were identified as the granular skeleton that provides strength to the material [14,17,84,86,97]. Well-graded soils were preferred since their packing structure allowed good space filling properties that increased cob density, and therefore its mechanical strength [14,17,84]. Clay was identified as the binder that brings cohesion to the material [84]. If clay content was too low, cob material crumbled [84,97,98]. Nevertheless, clay content also governs the drying shrinkage of the cob mixture. If clay content was too high, large shrinkage cracks weakened the material [84,97,98]. As for earth plasters [99], there is an optimum clay content for cob, thought to be around 20 % [9,16,81]. 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 [9,16,19,47,55,81,100,101]. However, most of the grading curves of earth collected in old cob buildings did not fit inside those grading envelopes [44,80,86,102]. Consequently, these grading envelopes failed to give full account of former cob masons knowledge.

Authors agreed with the fact that cob earth material was locally sourced. This was evidenced by the similarity between available soils next to heritage cob buildings and the earth used in their walls [10,31,38,85,86,93,95,102,103]. But more precisely, locally sourced earth materials meant that they could have been dig from the foundations of the building [98], a pond next to the new building or in a field surrounding the building [22,26,33,35,74,76,77,88,90,92,93,98,104–106], inside and immediately around the building during the construction [26,35,94], a field around the building [35,74,77,84,88,104,105], the cellar of the building [98,107], an earth quarry, located on the same municipality [95], a ditch cleaning [108] or a hollow way [74,77,109]. Another practice that appears to have been quite common, but difficult to attest, is the reuse of the earth of old cob walls [110,111]. It is then possible to precise what “local earth” meant for vernacular cob construction. It was an earth excavated on-site or, tenth [33] or hundredth [76] of meters or, at most, a few kilometres away from the site [95].

Earth excavation and transportation

Topsoil is rich in organic matter that decompose after implementation and created mechanical weaknesses inside earth walls [52,112–114]. It was therefore considered as unsuitable for cob construction [9,32,33,35,40,52,74,77,78,91,97,98,107,108,110,115–117] and it was cleared off before the excavation was carried out [40,74,77,107]. 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 [107]. The excavation was done by the owner and relatives [32,74,76,78,84,88,104,118–120] by hand, thanks to, for example, a mattock [34].

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 [35,98]. When not excavated on-site, earth was transported to the site by animal-drawn tumbrel and stored [74,104,105,121,122]. For a 20 m^3 earth lift, this corresponded to 10 tumbrel travels [88].

A unique source of material was sometimes not enough to complete the walls of the building [81]. As an example, when the earth excavated from the foundations of the building was not enough, another local material source was exploited (dug from a pong, a field, a hollow way…) 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 [24].

A first option was to realize the material supply at once, and all material sources could have been mixed together [107]. A second option was to realize the material supply separately for each lift [88]. Indeed, the amount of earth necessary to realize one lift was estimated to 20 m^3, which corresponded to several working days of hard labour for the working team [88].

Sometimes the poor earth quality required to temper it thanks to another material [108,110,120,121,123]. Thus another earth material source or aggregates could have been employed as an earth grading corrector [107,108,110,120].

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 [10,22,108,124] and to let the organic matter to decompose [108]. If rainfalls were not sufficient, the earth was wetted during winter [108]. More generally, earth was stored close to the construction site some weeks before the construction took place [88,105,110]. 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 [14,16,35,47,74,77,81,85,90,98,104,105,115,123,125,126], maximum particle size diameters is in the region of 50 mm (Table 3); (2) earth was loosened [16] thanks to a hoe [35,77,104,115], a mattock [126] or a spade [126], in order to break clods of earth; (3) earth was soaked days before mixing to make it more workable and to homogenize water content [34,35,47,64,74,77,88,98,104,105]; (4) earth was trodden by men [105] or by animals [88,124] to prepare soaked earth prior to mixing.

3.1.2 Water

As there was no water supply network at the time of their construction, cob buildings were more likely located near water sources [4,23,122]. Water was taken from the well of the farm, from a pond created by the excavation of the earth material [88,108] or from a ditch close to the construction [108,110]. 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 [74,104]. 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 walls drying [14,19].

3.1.3 Fibres

Although un-fibered cob was mentioned [9,14,34,84,107,118,127], cob technique was generally associated with natural fibre addition. Most commonly cited fibre employed for cob is straw (Table 4). According to Petitjean [74], during the 19th Century, 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 4). Since fibres were locally sourced [19,33], this diversity reflects the adaptations of the vernacular cob construction process by former builders to resources available in their nearby environment. Authors both referred to cut, or chopped, and uncut fibres (Table 3). Two modes for fibre length can be identified (Table 3): (1) small fibres (10-20 cm), fibres length being about equal to the size of a cob lump, (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 [14,100,107], (2) assist handling [9,10,16,22,26,31,84,100,117,118], (3) accelerate the drying process [9,14,19,26,35,100,107], (4) distribute shrinkage cracks throughout the wall mass [9,14,16,19,22,24,26,34,49,52,100,107,128,129], (5) enhance cohesion and shear resistance of the wall [9,14–16,19,26,31,49,100,129,130], (6) improve weathering resistance [10,100,130], (7) reinforce bond between lifts [108,117] and (8) wall angles [94,108].

Some authors [14,15,19] stated that fibres contributed to the thermal insulation of the wall. Yet, Keefe [9] argued that thermal conductivity reduction of a cob wall was significant only if a large amount of fibres was added to the mixture (about 25 % by mass). Fibre content of cob was generally between 1 to 2 % by mass (Table 3). In this case, thermal contribution of fibres seemed very limited. Anyway, the most important function of fibre is thought to be the distribution of shrinkage cracks [9,14,24,107].

3.1.4 Stabilizer

Fibres can be regarded as a stabilizer. As most of 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 [16,79,84,107,125]. Keefe [9] 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" [9].

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, casein [16,41,84,94,107,131]. Too little information are available about stabilization in cob literature, thus, the use of stabilizer is not detailed in this paper.

3.2 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 3.1, they were ready to be mixed together to form the cob mixture. Mixing took place on a flat and if possible hard [16,123] and impervious [126] surface. This surface was sometimes pre-wetted [16,126] and sometimes covered by a bed of fibres [16]. 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 [102,115,123,125], or in a continuous pile of earth (0.5 to 1.8 m large) all around the future building, alongside the walls under construction [74,77,88,104,105]. More rarely the mixing was done in a rough trough [125]. Earth was spread to form a layer some centimetres thick [74,104,105] to 10 cm thick [16,115,116]. Fibres (when required) were evenly distributed on the earth [10,16,74,77,88,90,102,104,105,115,116,125,126] and the whole was trodden by men [9,10,16,20,21,24,32–35,47,51,74–77,83,84,89,90,98,104,105,107,108,110,115,116,118,121,125,126,128,131–133] or by animals [16,31–33,35,47,74,77,83,104,107,128,132], generally horses [21,35,87,88,102,123,124] or oxen [21,35,102,108,110,121]. During mixing, more fibres (when required) were gradually added [75,102,121,123] and water content was corrected, based on guesstimate of the cob masons [9,10,14,16,34,102,116,123,126]. Manufacture water content of the cob mixture should bring it into a workable mix [16,47,85,87], i.e. into a plastic state [10,31,35,88,97,128,134,135]. Manufacture water content are in the region of 20 % (Table 3), which is in agreement with a plastic state. Average fibre content range from 1.4 to 1.7 % by mass (Table 3). This is in agreement with the optimum fibre content around 1% proposed by Danso et al. [130].

In order to ease the mixing, some authors referred to the use of forks [107,108,121,123], picks [102,125] and hoes [32,118,132] to stir the cob mixture [9,16]. When the mixing of the first layer was completed, the process was repeated several times to realize other layers over the first one [88,115,116] in order to create a pile of earth 60 to 100 cm thick [88,115] . The treading could last 1 – 2 h [124], a half-day [118] and up to 3 days [133]. 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 [24,31,116,118,126,128].

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 [9,10,14,16,64,100,126]. 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 [1,71,136–138]. Thus, mechanical strength and durability is enhanced if clay particles are evenly distributed inside the earth matrix [9,71,100]. Soils are usually organised in peds [114]. In order to evenly distribute clay particles inside earth material, it is then necessary to break those peds to mobilize clay [9,126]. 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 mixing realized on the "wet side" of the plastic state [9,10,14,47,55,100,126].

Besides kneading action, blending action of the mixing process allowed an even distribution of the constituent of the mixture [9,64,100,126]. Indeed, inhomogeneity would create weak points inside cob walls [126]. This was even more essential when another constituent was added to the cob mixture (sand, stones, fibres …). Fibres provided extra tensile-strength to cob walls and improved weathering resistance [9,10,14–16,19,26,31,49,87,100] but this was only true if fibres were evenly distributed [55,100].

3.3 Wall construction

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 [9,10,14,16,17,19,20,24,31,32,35,37,74,76–78,87,88,91,95,104,105,108,110,115,117,119,123–125,128,131,133,139–141]. Clods of earth were disposed so that they overhung the plinth on both sides of the wall by 5 – 15 cm [14,16,24,35,77,78,87,88,91,95,104,115,124,125,141]. Clods were often arranged in diagonal layers [16,31,87,111,115,125], by, for example, an angle of 35 – 45° [31,111]. Sometimes fibres were placed around each clod [26,134,140] or between each 6 to 8 cm layer of clods [22,31,32,35,76,117,134,140]. The use of wood dowel between each clods [108] and the use of bed of stones and/or tiles between each layers of clods [31,108] were also mentioned. Once in the wall, clods of earth were compacted by the trampling of the craftsman who worked on the wall [14,16,17,20,46,54,87,100–102,125,140], by hand [47,84,131] and/or with a tool (fork, stick) [10,14,16,24,54,87,88,100,101,140]. As the cob mixture was implemented in 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 [14,24,26,35,74,77,95,104,115,123].

In the United Kingdom several authors referred to a “quick process” by opposition to a “slow process” [9,22,54,142]. 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 [22], 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 [124] and cut in squares of 20-25 by 25-30 cm [24,35,131] with a sharp tool. These small rectangular blocks of cob could have been left to dry before they were placed in the wall [31]. They were then arranged in the wall in horizontal layers or in *opus spicatum* [31,32,35,76,98,124,131,140]. This technique is called g*azon* or *pâtons de mâssé* in Normandy [24,31,64,124] and c*aillibotis* in Brittany [35].

In case (c) the cob mixture was modelled by hand in a specific shape [82,83,111] (cylinder, ball, cigar, triangle) before to be stacked and compacted on the wall. *Massone* in Italy [52,143,144] and *Banco* in Africa [84,91,118,145] are some examples of this kind of technique. In Italy, unfibered cob mixture were modelled in the shape of cylinders called *massone* (8 – 15 cm in diameter and 30 – 40 cm long), rolled and covered by straw before they were implemented on the wall [52].

For case (d), several authors referred to the use of shuttering for cob wall construction [9,16,22,82,87–89,98,111,125]. This technique was called shuttered cob or puddled earth [9,22,87,107]. For example, shuttered cob is attested in Devon from around 1820 right up to 1914 [9,16]. According to Keefe [9], shuttered cob mixture is wetter than unshuttered one. Thus, in this case, drying times were long.

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 construction process. The height of wall done in a same time was limited. As a result, cob walls were a superimposition of successive monolithic earth raised, called lifts. A new lift was realized when the previous one was dry enough to bear the weight of the new lift without deforming [21,34,46,54,87,123,133]. 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 4). Wall thicknesses ranged from 10 to 150 cm with an average of 62 cm (Figure 4). In 17th century and earlier, wall thicknesses was 80 to 90 cm or more [22,32,77,125]. It decreased to 50 to 60 cm in 18th century [9,22] and reached 50-45 cm during the 19th century [9,77]. With time and improvement of the technique, craftsman were more and more confident and built thinner walls [9,10,14,16,22,32,34,35,77,103,125]. Slenderness ratio ranged from 0.5 to 1.6 with an average of 1.0 and a standard deviation of 0.3 (Figure 5). Slenderness ratio of lifts is proposed as an indicator of 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 5).

Earth consistency depended on its clay content, which differ naturally from one soil to another, and its water content, which was determined by the cob mason, according to his building practices [9,16,31,34,55,126]. To realize higher lifts and save time, clods of earth with a firm consistency were preferred, i.e. on the “dry side” of the plastic state [9,14,100,126]. This is in contradiction with the optimal mixing water content suggested in section 3.2 (“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 wet mixture inside the wall [14,47,100].

Fibres were employed to assist handling of clods and provide extra strength to fresh cob lifts and therefore built higher lifts [9,10,16,22,26,31,84,100,117,118]. The higher the water content was and the higher the fibre content should be. This relationship was illustrated by Saxton [100].

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 [21,35,54,85,87,91,101,102,126,128,134]. 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" [16,17,24,31,32,34,46,47,74,77,88,95,104,115,124,125,132,139–141,146,147] and sometimes a fork [35,76,78,108,121,146], a mattock [16], an adze [46,141], a saw [31,141], a shovel [49], a knife [47] or an axe [83]; (2) beating the faces of the wall thanks to a stick [26,31,35,47,88,95,109,124,139,140], hands [34,47], mallet [31] or stone [47] ; (3) scraping [134] overflowing material thanks to a fork [116,117,139,140] or a garden claw tool [139,140].

In case (a) (see section 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 [78,141]. Depending on the weather, it took place few days up to 3 weeks after the achievement of the lift [16,31,35,46,54,78,88,124,128,139].

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 [35,74,104]. This was one reason why large stones were removed from earth (see section 3.1.1). Another imprint left by the paring iron is the downward orientation of fibres [139].

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 [26,35,88,95,124]. The beating of the faces of the cob lift could be performed before and/or after trimming and all along the drying period [35,88,95,124].

An example of an elaborate lift face rectification was provided by Bardel and Maillard [35]: 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 [31,35,124].

When unrendered, the faces of the wall could have been smoothed by a trowel, hand or plaster float [88,108,120,133,134]. When rendered, faces of the wall could have been finger-marked in order to provide roughness and a better key for the plaster [108]. Rectification process determined the final shape of the wall. It could have been straight [94] or tapered [24,31,34,47,78,88,95,108,116,139,140,144] to provide more stability to the wall.

3.4 Drying

3.4.1 Drying time

Average drying times of a cob lift ranged from 11 to 21 days (Figure 6), depending on climate [9,24,31,34,35,47,49,76–78,85,88,97,104,105,116,118,123,125,139]. Then, the estimated time necessary to achieve cob walls, excluding "quick process" (see section 3.3.1), ranged from 3 to 20 weeks [21,22,24,105,125,131].

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" [14,19,21,26,35,74,104,107,124,125,139]. The implementation of cob on "dry side" of plastic state could accelerate the drying process. It was also suggested that fibres played a role to ease drying by channelling water from the core of the wall to its outer face [9,14,19,26,35,100,107]. Anyhow, cob walls had to be dried before the first frost to avoid damages [108].

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 manufacture water content of cob mixtures, high clay content and high manufacture water content leading to high shrinkage rate [9,100,126]. Several strategies were employed by former 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 (see section 3.3.3).

Another strategy was to use a cob mixture constituent as "shrinkage crack barriers". This constituent could have already been present inside 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 7). Layers of fibre, of stone or a course of adobe laid inside or between each lift [9,34,106,128,139] can be interpreted as "shrinkage cracks barriers" [34,128] (Figure 7). The aim of those barriers was to stop the expansion of shrinkage cracks thus avoiding their coalescence and therefore the development of large cracks [9,16].

This distribution of shrinkage cracks throughout the wall mass is well documented for fibres [9,14,16,19,22,24,26,34,49,100,107,128,129]. Tensile strength of fibres embedded in the cob matrix is a supplementary factor that participated to the resistance to crack opening [9,100,129,148,149]. When enough gravel was present in the earth material to contain shrinkage cracks, fibre addition was not necessary [35].

4 Discussion

4.1 Proximity of earth construction processes

Compressed Earth Bloc 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 [96,107]. A confusion comes from the use of shuttering for both rammed earth and shuttered cob [17,139]. 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 [17,107].

Wattle and daub, plasters and adobe mixtures are prepared in a similar way to wet cob mixture [150]. However, maximum particle size diameter is higher for cob mixture than for wattle and daub, plasters and adobe mixtures [9].

Wattle and daub is quite different from cob since earth is infilled in a timber frame and do not play any structural role [32] as well as plasters that are overlaid on wall face. It should be noted that some authors related the use of both cob and wattle and daub inside the same building [35,140].

Adobe and the cob process variations that consist in stacking cut or modelled plastic elements (case b and c, section 3.3.1) are quite similar, but adobes are dry implemented and require to be grouted with a mortar, whereas cob elements are implemented without mortar [32,35]. It should be noted that some authors related the use of both cob and adobe inside the same building, or next to each other [9,106], or together with an alternation of courses of adobe and cob [34].

Proximities between cob and other earth construction processes can be drawn at mixture and implementation stages (Figure 8). 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 8).

4.2 Identification of key points of cob process

This bibliographical analysis allowed us to identify three key points in cob construction process: (1) the mixing, since constituents of cob mixture should be evenly distributed, (2) the consistency of the cob mixture during implementation, since it should not subside too much in order to build higher lifts and (3) the management of shrinkage cracking, since no structural damage cracks should propagate inside cob walls (Figure 7). Considering that 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 (particle size distribution, clay content, clay activity, maximum particle size).The variety of strategies employed by former cob masons at each stage of cob process is illustrated in this paper (Figure 3) and it is possible to estimate that, at least, hundreds of variations existed for this process. In addition to technical constraints, cob construction had to face two major social constraints: (1) it was a slow process, since it took months to build the walls and (2) it was a labour intensive process thus requiring mutual aid system to make it competitive. Those constraints were not adapted in the Western societies of the 20th century and this enforced cob masons to develop mechanization and prefabrication.

4.3 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 3.3.2. 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.

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

Plinths of heritage cob walls are made of stones and earth or lime mortar [17,30,35,41,46,54,74,78,87,88,102,104,125,126,151] that drove capillary rise. Consequently, cob walls were exposed to humidification by capillary rise. If excess water is not evacuated from the wall, water content of the cob wall can rise and lead to poor thermal comfort and/or structural damages [9,16,30,87,152]. 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 [10]. The first mention of efficient damp proof courses made of bitumen cardboard concerned cob houses in the beginning of the 20th century [10,15]. The use of cement concrete in lieu of stone masonry for the plinth during the 20th century also participated to the protection in the cob walls from capillary rises [50,78,153].

Prefabrication of cob elements is a way to reduce the wall fabrication time [53]. Plastic elements of earth cut or modelled (case b and c, section 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 [21], 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 [94,154,155]. Cob mixture was casted in a mould that contained two hooks attached to three wooden pieces disposed on the bottom of the mould. Hooks were used to handle cob elements. Cob elements were unmoulded 24 h after casting and left to dry for 1 month. Height of the prefabricated cob elements was 50 cm, 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 [94,154,155].

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 [125]. The author stated that a power-driven “pan-mill” has been tried with success. Since, attempts have been made to mix cob, using machine such as concrete mixers [9,19,64,100,126], mortar mixers [9], vertical shaft mixer [31,94,154], rotavator [9] and clay brick mixer [52]. The kneading action of most of those machines was too little to force the straw and clay into contact. Thus, they required a higher manufacture water content, which increased the drying time. Those machines are considered as inappropriate for cob mixing [9,19,64,100,126]. Another mechanized technique developed in England consist in treading the cob mixture thanks to the wheels of a digger and in stirring it thanks to the digger bucket [9,14,19]. The mixing action of the digger is judged satisfactory but, as for other mechanized techniques, it required higher manufacture water content. It was then necessary to let the cob mixture to dry for a while before implementation [9,14].

New mixing and implementation methods were developed in the USA during the 1980’s and 1990’s [50,55,64,153]. 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 [156].

Joce [21] did a clear distinction between an old-fashioned cob method and a modern one with prefabricated elements. In fact, it is quite difficult to draw a line of demarcation between an old cob process and a modern one. As highlighted above, innovations concerned the past period of the cob process as it concerned the modern period. Modern cob is in the continuity of vernacular cob.

4.4 Cob and society

Social, economic and technical evolutions of societies had a great impact on the evolution of the cob process [4,42,76]. Until early 20th century in Europe, masons moved by foot or by bicycle and building materials were transported by animal-drawn tumbrel [74,77,105]. Consequently, masons had to use locally available materials and had a range of action restricted to a few kilometres [74,75,77,80,87,122]. This isolation was more dramatic in marshlands [27,88,110]. Cob construction process know-how was orally transmitted generation after generation [9,22,24,31,43,46,118] and the limited transportation means did not foster the exchange of know-how between cob masons. This generated local practices and habits for construction [42,75,77,87]. This is illustrated by the variety of names given to cob mixture in Brittany that were different from a town to another [75,76]. 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 [42,80,87,98,110,119,125,126].

Cob site work required an important workforce [154]. Usually, a skilled cob mason, eventually accompanied by 1 or 2 employee or apprentice, conducted site operations [74,78,87,105]. Workforce was supplemented by the owner helped by his family and his neighbours [74,88,104,120]. Sometimes cob houses were self-build by the owner [32,78,84,87,94,118]. In all cases mutual aid brought by the neighbours' workforce was essential to face cob site work [118,119,154]. 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 [76,90]. Rural migration depleted available workforce and know-how, and commodification broke rural solidarity [24,35,43,97,118,119]. Without mutual aid system, labour charge became unaffordable for a part of the rural population [1,154]. Mechanization of the process was an answer to this issue [1].

In Europe, before 1900, because cob houses were cheap to build, it was the unique affordable construction for a part of the population [1,74]. For them it was therefore not a choice but a constraint that highlighted their social class [157,158]. Therefore, for a large part of the population, cob was synonymous with poverty, archaism, unhealthiness and low strength [9,26,38,42,78,84,88,97,98,144,154]. This is why where stones were available it was preferred to earth as a building material [24,35,80,104,159]. Earth was considered as a default material choice [74]. 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 [4,14,17,32,38,87,154,159–161]. Nevertheless, with the introduction of industrial building materials (brick, cement), regarded as a social symbol of modernity, cob felt into disuse [9,26,42,84,97,125,144,157].

Finally, political decisions also had a great influence on cob construction. For example, the old regime land law in Brittany [98,119,160] and an old tax on bricks in the United Kingdom [22] 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 [16,87,97,126,162]. Building regulation is still an obstacle for modern earth construction [2].

4.5 The future of cob process

Vernacular cob construction has many environmental, social and health benefits (see section 1) and is therefore a source of inspiration in order to reduce the impact of modern building sector. Nonetheless, this slow process was time consuming and required a large workforce, which is inappropriate in West modern economies [1,14,52,53,163]. 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 (see section 4.3). 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 [10,81], forcing its particle size distribution into a grading envelop predetermined in laboratory and/or addition of hydraulic binder [164–167]. These solutions reduce the environmental benefits of cob [2]; (2) adapt the process to the material [2,14,168]. This solution optimizes the consumption of natural resources and relies on the expertise of skilled craftsmen, architects and on performance 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 cob environmental and social benefits. A balance has to be found between a zero-emission vernacular material and a fast implemented and strengthens material. The future of cob will be the result of an optimization of the economic and environmental sustainability of the process.

5 Conclusion

Better describing and understanding cob technique will permit an appropriate care and repair of cob heritage buildings and to 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 evidenced its adaptation to different soil natures, climates and social needs across the world. Cob technique participates to the diversity of earth construction processes. This diversity is a key to promote the use of locally available and unprocessed construction materials, as it broaden 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 written materials exists on the description of cob vernacular process. To go further on the description of this process, it is necessary to describe and analyse existing cob heritage buildings. Scientific methods should be developed to go on with this rediscovering movement.

6 References

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Caption for figures

Figure 1. The oldest attested cob building of Brittany, located in La Chapelle-Thouarault and dating back to 1608 [35]. *This picture was taken in 1975 (Service de l'Inventaire du Patrimoine Culturel © Région Bretagne).*

Figure 2. Earth construction processes classification, adapted after [9,17,71]. *Distinction is made between load bearing and self-sustaining techniques (bearing) and non-load bearing techniques (non-bearing). (W_m = manufacture water content, W_{OP} = optimum Proctor water content; W_P = water content at plastic limit; W_L = water content at liquid limit)*

Figure 3. Summary of vernacular cob process. Water contents are to be regarded as order of magnitudes. (elements in brackets are optional; W = water content, W_L = water content at liquid limit, W_P = water content at plastic limit, W_{SH} = Water content at shrinkage limit)

Figure 4. Cumulated citations of minimum (Min) maximum (Max) and average values of cob lift height and cob wall thickness.

Figure 5. 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).

Figure 6. *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.*

Figure 7. 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)

Figure 8. Cob process stages and related earth construction processes

Table captions

Table 1. Geographical distribution of cob construction process description in bibliographical references. France and United Kingdom together represent 72 % of the bibliographical references.

Table 2. Vernacular names of cob construction process.

*Table 3. 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 manufacture water content by weight of cob mixture according to literature.*

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Figures with captions

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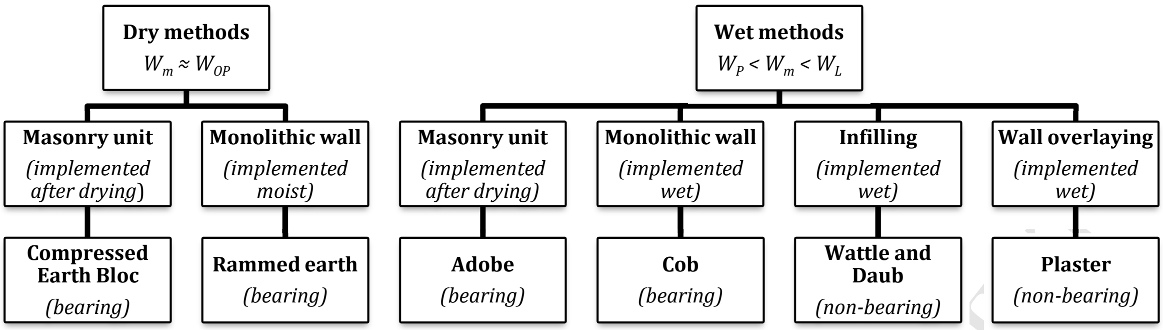

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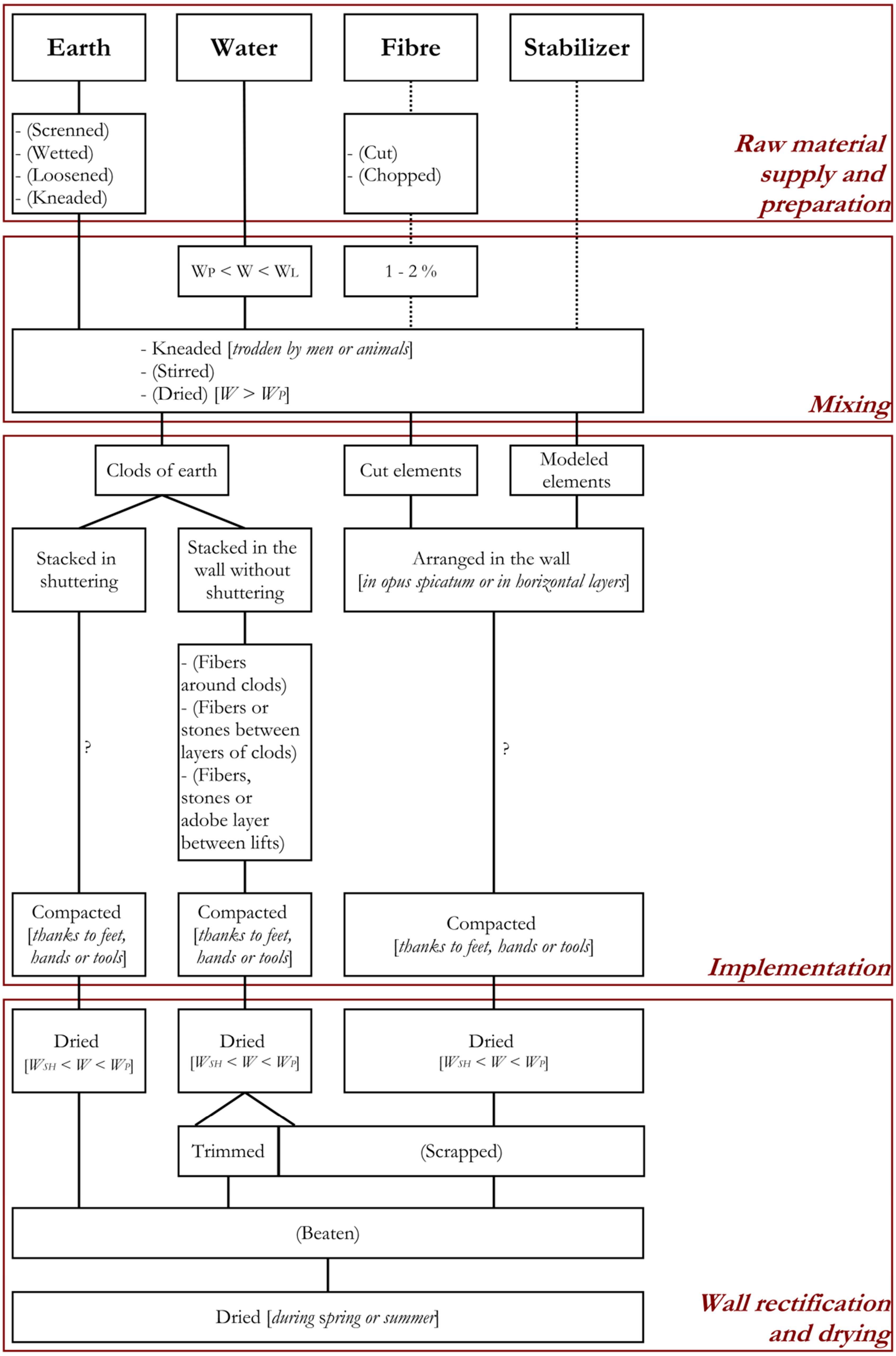

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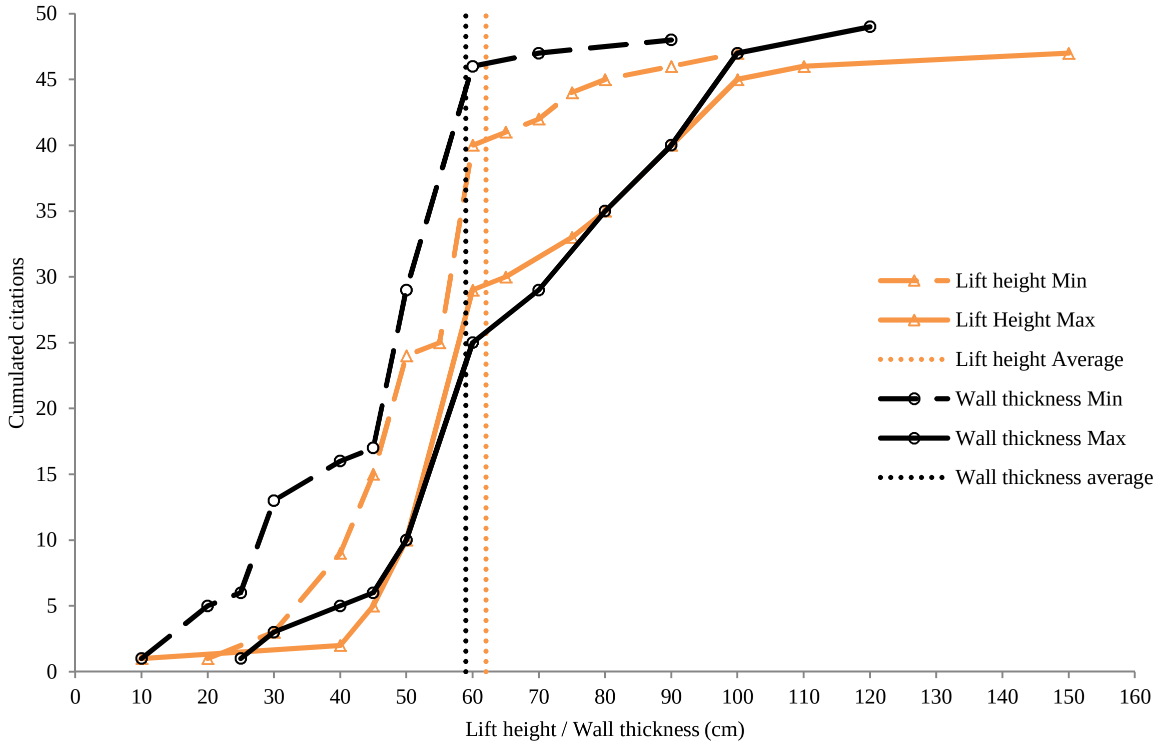

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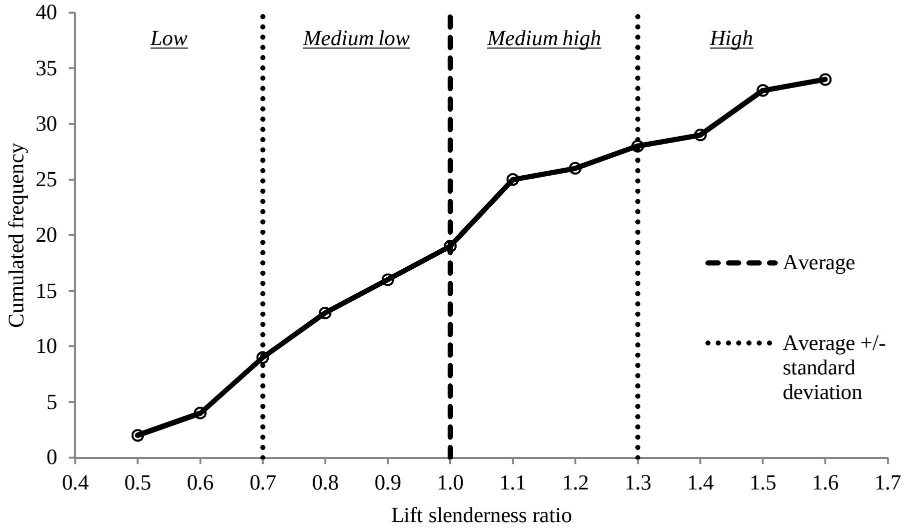

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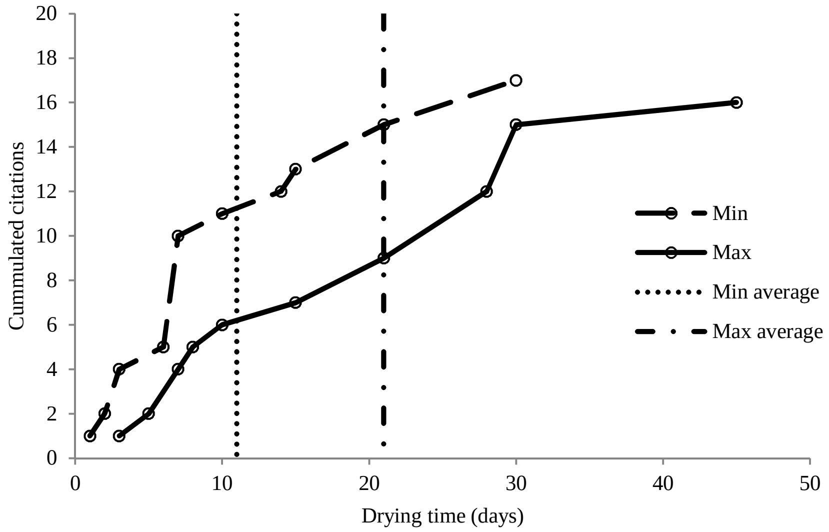

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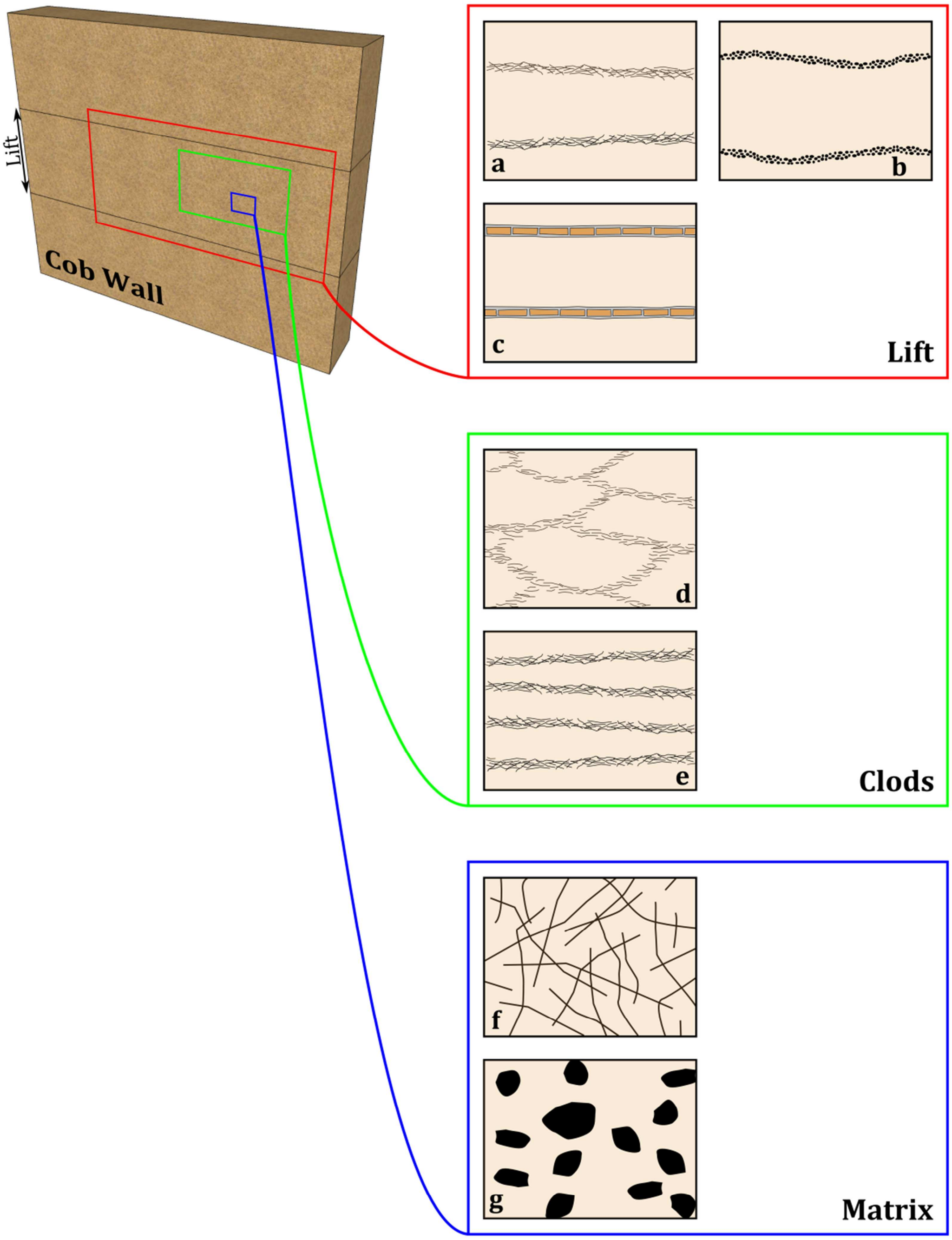

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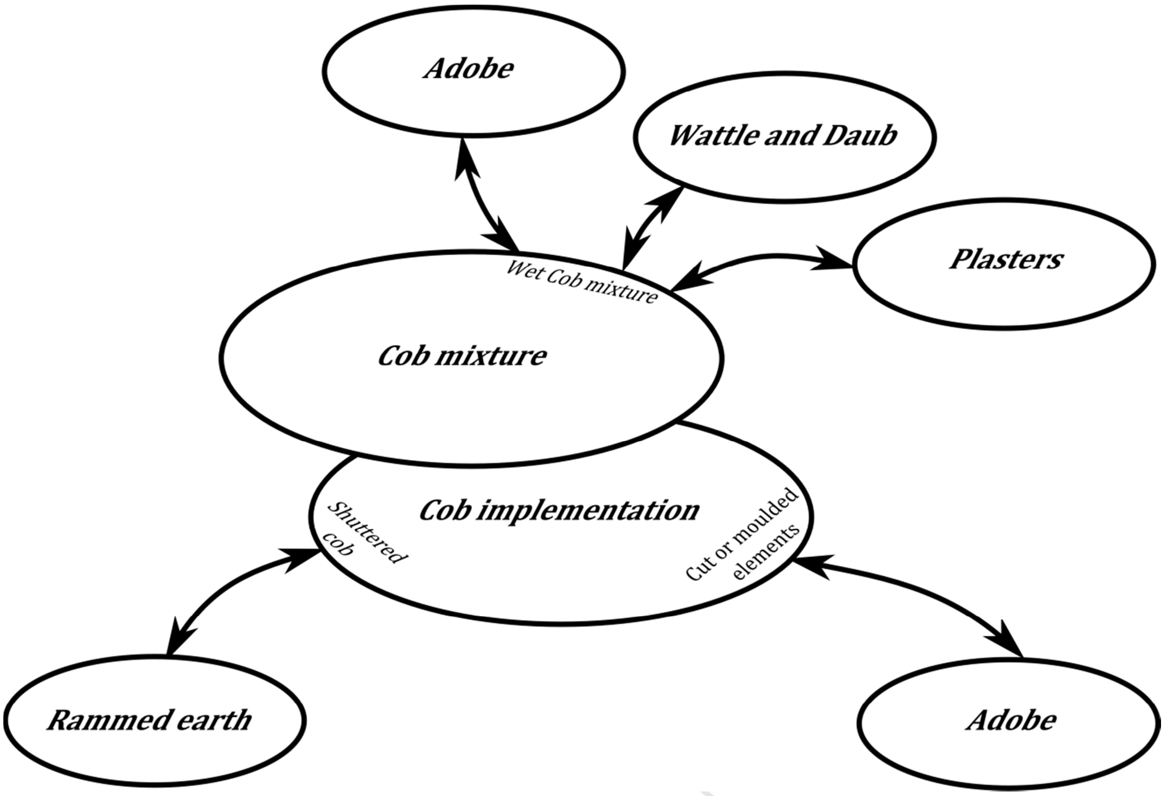

Figure 8. Cob process stages and related earth construction processes.

Tables with captions

Table 1. 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	[34,128,131]
Belgium	1	[73]
Burkina Faso	1	[120]
Czech Republic	3	[82,83,111]
France	59	[18,26–29,31–33,35,43,57,62,74–77,80,85,88–90,92–98,104,106,108–110,116,117,119,121,124,134,139,140,146,154,155,157,159,160,169–180]
Germany	4	[10,15,30,91]
Ghana	1	[131]
Hungary	1	[36]
India	3	[34,131,133]
Iran	1	[47]
Ireland	2	[107,181]
Italy	3	[52,143,182]
Ivory Coast	1	[118]
Madagascar	1	[94]
Mali	2	[145,183]
New Zeeland	3	[37,51,55]
Nigeria	2	[79,127]
Senegal	1	[118]
Slovakia	1	[83]
Sudan	1	[131]
Tajikistan	1	[34]
Togo	2	[84,118]
Turkey	1	[36]
Turkmenistan	2	[34,184]
United Kingdom	44	[14,16,17,20–25,38,41,42,44–47,49,54,78,81,86,87,100,102,103,105,107,115,122,123,125,126,151,152,162,185–193]
United States of America	4	[37,50,91,153]
Yemen	1	[47]

984 *Table 2. Vernacular names of cob construction process.*

Country	Local names	Reference
Afghanistan	pakhsa	[34,36,101,128]
Belgium	tourton	[73]
Czech Republic	nakladani, valek, války	[36,83,111]
East Africa	daga	[36]
France	bauge, bigôt, bouzillage, caillibotis, coque, daube, gachcoul, mâsse, mâssé, mur d'argile, paio-bard, paillebart, paillebort, palho-bard, pâtons de mâssé, terre, torchis	[18,24,27,31,35,36,95,105,108,110,121,150,173,179]
Germany	lagenlehmbau, lehmweller, wellertechnik	[15,36]
Hungary	valgoy	[36]
Iran	chineh	[36,101]
Iraq	tawf	[36]
Ireland	tempered clay	[107]
Italy	atterati , maltone, massone,	[36,144,194]
Madagascar	tamboho, tovam-peta	[36,94]
Portugal	terra empilhada, terra modelada	[36,194]
Spain	chamizo, muro amasado, pared de mano, terra apilado, terra amassado, fang	[36,194]
Slovakia	lepanice, nakladana stavba, vykladanie, valok	[36,82,83]
Sudan	jalous	[131]
Turkey	pahsa	[36]
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	[9,14,17,22,46,87,101,107]
West Africa	banco, banko, terre de bar, swish	[36,120,131]
Yemen	zabour, zabur	[17,36]

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*Table 3. Maximum particle size diameter, fibre type, preparation and length, fibre content (when data are given for 1 m^3 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 manufacture water content 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 (%)		Manufacture water content (%) by weight
					Minimum	Maximum	
[169]		straw	Yes				
[169]		hay	Yes				
[87]					1.3		
[75]		furze	Yes	10 – 15			
[75]		straw	Yes				
[98]	80 – 100	straw	Yes				
[116]		straw	Yes	15 – 20			
[119]		straw	Yes				
[131]		straw	Yes				
[97]		straw	Yes	15 – 20			
[76]		straw	Yes	15 – 20			
[117]		straw	Yes				
[78]		straw	Yes	40			
[105]		straw	Yes	60			
[104]		straw	Yes	60			
[24]					1.6*		
[47]					0.3*	1.0*	
[88]					1.6*		
[16]	50						
[100]					1.0	2.0	
[126]	50 – 60	straw	Yes				
[172]		straw	Yes				
[162]					1.5	2.0	
[55]		straw	No				
[90]		straw	Yes	15 – 20			
[124]					1.6*		
[25]					2.0		18
[15]		straw	No	70			
[173]		straw	No				
[173]		hay	No				
[91]		straw		40 – 50			
[81]	50						18 – 25
[74]		heather	Yes				
[95]					1.6*		
[102]		straw	Yes				
[9]		straw	No		1.0	1.5	
[54]		straw	Yes				
[85]							10 – 20
[14]	50						18 – 25
[10]		straw	Yes	30 – 60	1.4*	1.8*	
[135]		straw	Yes	30 – 50	1.3*	1.9*	
[79]		straw	Yes				
[147]							15 – 30
Average					1.4	1.7	-

991 *Table 4. Number of citation and bibliographical references of different fibre type employed with cob.*

Fibre	Number of citation	References
animal hair	4	[14,88,107,124]
barley straw	8	[14,16,22,97,102,107,116,126]
bean pod	2	[76,98]
broom	5	[22,33,35,74,95]
cow parsley	2	[14,107]
fern	5	[22,24,31,33,140]
flax	3	[14,19,107]
furze	11	[14,31–33,74,75,98,104,107,108,119]
grass	6	[14,24,88,95,104,107]
hay	22	[14,16,22,24,26,31,35,74–76,88,95,98,104,107,110,121,124,140,169,173,179]
heather	18	[14,19,22,24,32,33,35,41,74–76,98,104,106,107,119,139,140]
leaf	1	[118]
moss	2	[14,107]
needle	1	[108]
oakum	3	[75,76,98]
oat straw	12	[14,19,31,64,74–76,89,98,104,107,119]
quack grass	2	[14,107]
reed	2	[19,107]
rice straw	2	[64,183]
root	1	[118]
rush	8	[14,22,24,31,88,95,98,124]
rye straw	7	[10,15,19,26,35,64,74]
sedge	5	[14,107,108,110,121]
straw	47	[9,20,22,24–26,32,33,35,46,47,49–52,55,74–77,83,84,87,90,95,98,100,105,106,108,110,115,117–119,121,123,128,131,140,144,153,162,169,173,179,183]
stubble	2	[87,92]
twig	6	[14,16,24,26,35,107]
vine shoot	1	[139]
wheat straw	13	[10,14–16,19,31,64,78,89,97,102,104,126]

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