Chapter 1
General Introduction

Erwan Hamard, Antonin Fabbri, and Jean-Claude Morel

Abstract Earth is a building material excavated from the subsoil which is employed by Mankind since the Neolithic time all over the world. Various building techniques are used with earth, to build monolithic walls, to produce bricks, as infill of walls or as plasters or mortars. Earth architectures undergo a rebirth since the 2000s because they are a way to save natural resources and energy and to provide a good indoor comfort and a good social impact. Nonetheless, earth building sector faces many challenges to be considered as a contemporary material. This book, which is produced in the framework of the TC 274, will focus on the estimation of the parameters which are necessary to properly design earthen constructions. After a general introduction on earthen materials and constructions, the state of the art on the material characterisation techniques, the assessment of hygrothermal performance, the mechanical and seismic behaviors and the durability will be presented, each in a dedicated chapter. A critical review of the standards which are used for earthen material will be presented in the last chapter.

Keywords Earth material · Resource · History · Building techniques · Environmental impact · Social impact · Modern construction

1.1 The Origin of Earth

Most of earth materials are excavated from subsoil horizons and some of them are excavated from alterites or soft rock deposits. Topsoil is sensitive to shrinkage and decay and is therefore unsuitable for building [17, 28]. These materials are

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produced by geological, weathering and pedological processes. These processes are summarized hereafter.

When exposed to the surface, the physicochemical equilibrium of rocks is in imbalance with their new environment, and rocks are exposed to weathering. The effect of weathering tends to decrease from land surface downward to the unweathered bedrock, creating a weathering profile. Weathering generates loose material that are easily mobilized by ablation processes, i.e. colluvial, alluvial, eolian and glacial processes, to form superficial deposits. Superficial deposits differ from soil since they are subjected to sedimentary processes (erosion, transport and deposition).

When superficial deposits remain stable over time, they are affected by weathering and pedogenic processes. These processes, over time, tend toward the complete transformation of a parent material into more stable components and structures. 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. Soil is an accumulation of parent material weathering products and biota degradation products. Fractions 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. Peds facilitate the downward movement of water and colloids inside soil and the differentiation of soil in pedological horizons. Soil formation is a 3-dimensional balance among gains, losses, internal redistribution, and chemical and physical changes.

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. A vertical cross-section of weathered materials from ground surface to unweathered bedrock, according to several disciplines' definitions, is proposed in Fig. 1.1. The possible material sources for earth building is highlighted on this figure. Before the invention of excavators, excavation was carried out by hand. This is why, in the past, excavations concerned the first(s) soil horizons of the subsoil, just beneath the topsoil.

1.2 Historical Overview

Since, at least, the very beginning of the Neolithic revolution, human beings have employed earth associated with timber, fibres and stones to build their shelters and dwellings [37]. Earth as a building material is attested in most of Neolithic centres of origin, like, for example, the fertile crescent [1, 11, 37], Mesoamerica [10] and China [47]. It was first used as mortars, as plasters and as infills of timber frame structures (wattle and daub) (Fig. 1.2) [1, 37]. During the early Neolithic, at least in the Near East, two new techniques are attested on archaeological sites. The first one consists in piling wet clods of earth to build a wall (cob). When cob technique emerged, it

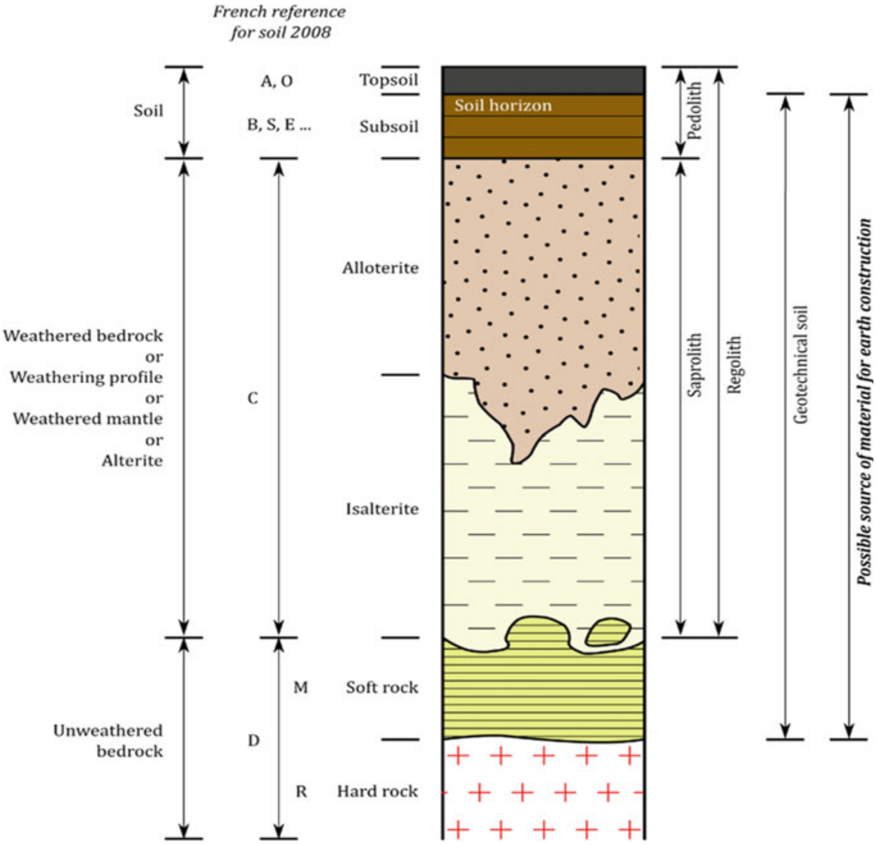

Fig. 1.1 Vertical cross-section of weathered materials from ground surface to unweathered bedrock, according to several disciplines definitions [19]

tended to replace wattle and daub [37]. The second building technique appears after cob and consist in laying sun-dried bricks shaped by hand (adobe). In western Near East, when adobe technique emerged, it largely replaced cob [1, 5, 37] (Fig. 1.2).

During the Iron Age, about six millennia after the invention of adobe, a new earth building technique, attributed to the Phoenicians, is attested in the West Mediterranean area [5, 22]. It consists in compacting earth, layer by layer, inside a formwork (rammed earth). Some attempts of compaction of earth in smaller moulds to make bricks (Compressed Earth Blocks, CEB) are recorded in the nineteenth century. But CEB were more commonly used after the development of powerful and functional presses, like the ClNVA-RAM designed by Raul Ramirez at the CINVA center in Bogota in 1952 [33]. The last commonly used earth building technique arose in Germany after 1920 and was designed to improve the thermal insulation of walls by significantly increase the fiber content of wattle and daub mixtures, in order to reach

Fig. 1.2 Archaeological evidences of earth building techniques in the ancient Near East, adapted from [38], reproduced with the kind permission of the author (© Martin Sauvage, CNRS, UMR 7041, Nanterre)

densities lower than 1200 kg.m^{-3} [43]. It consists in binding bio-based aggregates or fibers with an earth slip (light earth).

These techniques have spread from their territories of invention and have been adopted by other groups of people. For example, adobe technique spread from the Near East across the Mediterranean sea from the Neolithic to the Iron Age period [6]. The adoption of building technique on a new territory requires favorable natural conditions, i.e. suitable soil, adapted water supply and climate conditions. Nonetheless, the succession of several techniques on a same territory, like for example in the Languedoc region (south of France), where cob was replaced by adobe in the Iron Age and adobe by rammed earth in the Middle Age [4], highlights that natural conditions are not enough to explain the propagation of a technique in new territories. The cultural and social acceptability is also a major factor. This acceptability is difficult to set, but the emergence of a new technique is favored if it meets a need, raises the social esteem, if it is affordable and not imposed by an authority [4, 5].

When adopted, people become more and more familiar with the technique and they adapt it to their natural environment and with their needs. This adaptation is illustrated, for example, by the cob walls in England that shift from self-standing walls in the fourteenth century to load-bearing walls in the seventeenth century [23]. It leads to the creation a wide variety of local construction cultures [9]. These

Fig. 1.3 Ksar of Aït-Ben-Haddou (Morocco) inscribed in the UNESCO World Heritage List (© Marc Marlier)

construction culture are not immutable, they appear, evolve, expand and disappear, depending on resource availability and social changes. Construction cultures are the result of vibrant processes and earth building, since its 10,000 years of existence, has experienced many golden ages, disuses and renaissances. Earth built heritage reflects the outcome of this long evolution. This heritage highlights the appropriation of earth as a building material by cultures all over the world and in all periods since the Neolithic time [7, 42] (Fig. 1.3). For example, 20% of cultural sites of the UNESCO World Heritage List are fully or partially made of earth and it is estimated that about one third of the word population lies in earthen houses [21].

In the middle of the twentieth century, a slow awakening of the impact of human activities on nature began. Since then, the consequences of the consumption of natural resources, fossil energies, greenhouse gas emissions and the artificialization of natural spaces, due to the lifestyles of Western societies, have revealed their unsustainability. Today, there is a strong societal desire to promote solutions in harmony with nature. It is in this context that earth building, like other natural and low-process building materials, is experiencing a new renaissance [24].

1.3 Classification and Definition of Earth Building Processes

A classification of earth building processes is proposed in Fig. 1.4. A first distinction is made to classify earth-building processes, regarding the hydric state of the mixture during their fabrication: plastic, solid and liquid. For plastic-state processes, earth mixture is employed in a plastic state and mechanical strength of the material is provided through drying shrinkage densification. For solid-state processes, earth mixture is employed at an optimum water content and mechanical strength is provided through compaction densification. For liquid-state process, an earth slip is used to bind plant particles. A second distinction is made regarding the type of implementation and the hydric state of the material during the implementation. It can be implemented right after the mixture fabrication, i.e. wet or moist, or after drying, i.e. using prefabricated elements. A final distinction is made regarding the

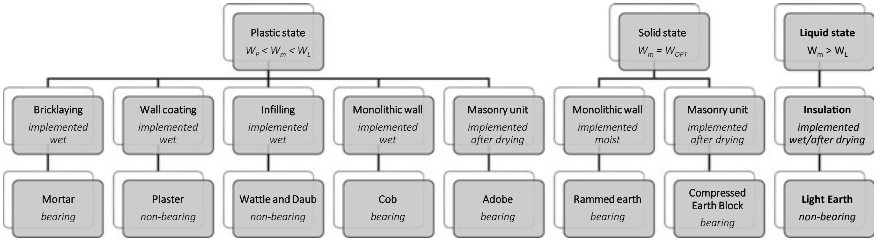

Fig. 1.4 Earth construction processes classification, adapted after [13, 19, 23, 25]. (W_m = water content of manufacturing stage, W_{OPT} = optimum water content; W_P = water content at plastic limit; W_L = water content at liquid limit)

structural role of the earth element that can be a load-bearing/freestanding wall or a non-load-bearing element.

Using this classification, it is possible to define earth construction processes as follow (cf. Fig. 1.5):

- ***Mortar***: earth mixture carried out at plastic state, implemented wet, in order to lay bricks or stones.
- ***Plaster and render***: earth mixture carried out at plastic state, implemented wet, to coat indoor or outdoor surfaces, respectively.
- ***Wattle and Daub***: earth elements mixed with fibres in a plastic state, implemented wet, in order to fill a timber frame load-bearing structure.
- ***Cob***: earth elements mixed in a plastic state, stacked wet, 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.
- ***Rammed Earth***: earth compacted at optimum water content layers by layers inside a formwork in order to build a monolithic and load-bearing or freestanding wall.
- ***Compressed Earth Block*** (CEB): masonry unit compacted at an optimum water content, dried and laid in order to build a load-bearing or freestanding wall.
- ***Light earth***: earth slip at liquid state mixed with a large volume of plant particles (dry density less than 1200 $kg.m^{-3}$) in order to provide an insulation material, carried out on-site or prefabricated.

These simple definitions permit to distinguish one technique from one other, but they do not reflect the large diversity of these processes. For example, it can be estimated that hundreds of variations exist for cob process [18]. Every technique should be more considered as a family of processes with large variations.

Among these variations, some can be regarded as “missing link” between these techniques. Adobe and the cob process variations that consist of stacking cut or modelled plastic elements are quite similar, but adobes are implemented dry and require to be grouted with a mortar, whereas cob elements are implemented damp without mortar. Shuttered cob has great similarities with rammed earth, but, for rammed earth, shuttering is employed to make the ramming process efficient,

Mortar between CEB *Plaster*

Wattle and Daub *Cob*

Adobe *Rammed Earth*

Compressed Earth Blocks (CEB) *Light Earth*

Fig. 1.5 Earth building techniques (© Univ. Eiffel, ENTPE, NOVA Univ. Lisbon) whereas, for shuttered cob, shuttering is employed to avoid the trimming of the faces of the wall and therefore accelerate the wall faces rectification stage [18]. This proximity is the result of a shared history, every technique arising from a pre-existing one. There is thus a continuity between all earth construction techniques and they should be considered as a whole, and not as separated processes.

1.4 Why Building with Earth?

1.4.1 Saving Natural Resources

In the Western countries, the construction sector consumes a large volume of natural resources and is responsible for about 50% of wastes production in the European Union [26]. These wastes have a negative environmental impact and it is increasingly difficult to find suitable landfill areas. Among these wastes, about 75% are soils and stones [2]. These materials could be reused for earth building. For example, in Brittany (France) it was estimated that 23% of landfilled earth, i.e. 0.6 million tons every year, are suitable for earth building. The reuse of this high-quality building material would enable the construction of 52% of individual housing of Brittany [20]. This resource is widely available and is produced during earthworks, usually located near construction sites, limiting transportation. The reuse of those wastes for building might save natural resources required for conventional building material production and avoid landfilling.

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 [46]. Extraction of earth for construction might affect multi-functional roles of soil. Management of the consumption of this resource should therefore be carefully considered. If unstabilized, reversible clay binding allows a complete and low-energy reuse of earth at end of life. The unstabilized earth construction allows an almost infinite reuse of the material for construction or its return to agricultural land.

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.

1.4.2 Energy

Embodied energy together with operational energy of the building sector represent approximately 40% of global energy use [27, 36]. As a consequence, the building sector is a major producer of greenhouse gases that contribute to climate change.

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 [27, 32, 35]. In order to pursue energy saving effort, the next challenge for the building sector will be the reduction of embodied energy for new buildings and the development of low-impact insulation solutions to retrofit existing buildings. This involves good maintenance of existing buildings and the use of construction materials with low embodied energy [15, 16].

Historical builders mainly had animal energy and unprocessed local materials for construction purpose. As a consequence, embodied energy of earth built 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. For example, embodied energy of a wall made of earth is about 20 times less than this of a hollow cinder block wall [14, 23, 34]. As a consequence, earth construction is considered as a low greenhouse gas emitter.

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 [8, 31].

1.4.3 Indoor Comfort

Thanks to their high thermal mass, and their high hygroscopicity enabling water phase changes [39, 40], earthen walls buffer outdoor temperature variations. They are able to accumulate solar energy during the day and restore this energy during the night. 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 either to adsorb rapidly or release a significant amount of 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 [3, 29].

Some authors mention several other beneficial properties of earthen buildings such as: good acoustic properties, fireproof properties, non-toxic and non-allergic properties and even a capacity to adsorb pollutant from the indoor air. These features have, however, yet to be clearly demonstrated but are explored further in subsequent chapters.

1.4.4 Social Impact

Earth meets human construction needs for more than 10,000 years and left us an important and rich architectural heritage worldwide. This heritage has a high historical and cultural value and should be properly maintained. This implies the preservation of a vibrant vernacular know-how. The vernacular construction strategies developed by past builders can be regarded as an optimum use of locally available resources under local natural conditions. With the loss of the vernacular know-how, the built heritage is the last witness of these strategies. Beyond its historical and cultural value, heritage should be also considered as a source of inspiration for modern sustainable building.

On earth building construction sites, implementation is carried out by skilled craftsmen whose expertise is recognized by other actors of the construction [12]. 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.

In emerging countries, there is a strong demand for affordable houses in high urbanization rate areas as well as in remote areas. Conventional construction requires the importation and the transportation of materials whereas the use of local materials, like earth, significantly reduces construction costs [14, 41]. In high-income countries 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.

1.5 The Challenge for Modern Earth Building

Earth construction will play an important role in the modern sustainable building of the twenty-first 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 nonsense 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

Fig. 1.6 Examples of modern earthen constructions

and avoid repeating past mistakes. The future of earth construction should be a continuation of past vernacular earth construction.

Nonetheless, past vernacular processes are slow, time-consuming and require a large workforce, which is inappropriate in current Western modern economies [24, 44, 45]. In order to comply with this economic constraint, two options can be identified for earth: the recourse to self-build houses or the recourse to mechanisation and/or prefabrication. 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 earth process. Since the mechanical strength of earth is quite limited, for load-bearing walls, walls are quite thick and prefabricated wall elements heavy. Their transportation has therefore a high environmental and economic cost. To reduce the economic and environmental costs, the on-site prefabrication seems the more adapted. However, in specific context, like dense urban areas, external prefabrication processes, especially for non-bearing elements of smaller size, can be considered.

The earth 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, forcing its particle size distribution into a grading envelope predetermined in the laboratory and/or addition of hydraulic binder, this solutions reduce the environmental benefits of earth; (2) adapt the process to the material [30], 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 earth construction (Fig. 1.6).

In addition, the development of this ancestral building technique notably suffers from a lack of appropriate standards. In consequence, they are disadvantaged compared to conventional construction techniques. The lack of knowledge of the material behavior can lead to apply common procedures and solutions, which are suitable for other building materials but which may be not adapted or even harmful when they are applied to earth buildings. There is a strong need for highlighting the particularities of earthen material and providing tools and methods to properly assess their performance.

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 building 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. These alterations usually come from economic and regulation constraints of the building sector imposing to speed up the construction process and to strengthen the material. 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. 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. To this aim, ecodesign and Life Cycle Assessment methods should be considered.

1.6 Conclusion

The bibliographic study of this chapter underlines that a good understanding of the earthen constructions requires taking into account their large variability. A first reason of this variability is that the local soils are used as building materials. The local soils are variable depending on the geology and local conditions of the site. Each construction can potentially be built with a different material and cannot be totally included in an industrial process. Then partly to adapt the building technique to the different soils, several construction techniques have been invented, which is the second reason of the variability. This book, which is produced in the framework of the TC 274, will focus on the estimation of the parameters which are necessary to properly design earthen constructions. After a general introduction on earthen materials and constructions, the state of the art on the material characterisation techniques, the assessment of hygrothermal performance, the mechanical and seismic behaviors and the durability will be presented, each in a dedicated chapter. A critical review of the standards which are used for earthen material will be presented in the last chapter.

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