EARTH CONSTRUCTION MATERIALS: FROM PAST TO MODERN BUILDINGS

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1 INTRODUCTION

Earth, with wood and stone, is probably the oldest known building material in the world. It has been used in many areas and by most of the civilizations in history, with the oldest recorded case of its use in the construction field dating back around 10,000 BC, in Mesopotamia (Quagliarini et al., 2010).

Building with earth is common in all hot-dry, subtropical and moderate climates, with a major expression in less developed countries where the majority of such constructions are located (Minke, 2006). In advanced economies, earth was intensively used for construction until the end of the nineteenth century. After this date, concrete replaced these materials thanks to its exceptional properties (speed of implementation (coupled with ease of mechanization of implementation), low cost for high mechanical performances and durability, etc.). If concrete made from aggregates (mostly of natural origin) and cement did not pose any environmental problems (in particular in connection with its carbon footprint linked to the significant amounts of CO_2 emitted during the manufacture of cement), it is unlikely that researchers would once again be interested in natural materials, such as earth, as an alternative. However, the dramatic ecological situation in which the World finds itself at the beginning of the third millennium forces Man to reconsider how he consumes, and in particular how he builds. Thus, materials that have been abandoned for several decades, such as earth or bio-based materials, are attracting renewed interest, not only because of their low environmental impact (abundance, renewable materials in the case of bio-based materials, recyclability, low embodied energy, etc.) but also for their own specific properties, particularly from the point of view of habitat comfort (high thermal inertia of the earth, insulating property of bio-based materials and high potential for moisture regulation for both these types of material).

Thus, we are witnessing, today, a radical change in the reasons for using earth as a building material. In the past, and still today in some developing countries, earth has been used because of its low cost and abundance, which often gives it a very negative image as “the material of poor people”, whereas concrete would be the choice of the rich. But this image is changing and it is now for its numerous qualities that earth is being reconsidered as a pertinent material for construction in advanced economies, and especially in European countries like Germany, Italy, France and Great Britain or in newly industrialized countries such as India. Today, it is even fashionable to build with earth in France and, under the impetus of some architects, many public buildings are being built using earth.

Yet it is still difficult for earth materials to penetrate the construction materials market significantly, for several reasons. First of all, this material does not resist water. We will see later in this article how the builders of the past managed to circumvent this major drawback. In addition, in many countries, including France, a lack of regulations also hampers the development of earth construction. This need for standards will also be discussed in this paper. Finally, we will discuss how earth materials can be stabilized using mineral binders. This stabilization responds to two objectives: an increase in mechanical performance and an improvement in the water resistance of these materials. We will then discuss the relevance of using such chemical stabilization of earth materials more and more frequently.

2 CONSTRUCTION CULTURAL HERITAGE

Historically, the formulation and the manufacture of earth construction materials was achieved in an empirical way based on local constructive cultures often passed down from generation to generation by the builders who were also mostly peasants, exploiting earth for agricultural activities. These builders learned to adapt to the constraints of local materials and especially to the characteristics of local earth because, unlike what happens today, it was not possible to transport materials over long distances and it was not possible to improve the properties of earth that did not perform well for construction by adding chemical stabilizers. In particular, this led to a regionalization of techniques, of which France can be used as an example (Figure 1).

Indeed, Man adapted himself to the properties of the soil from his region and this oriented his choices concerning the technique used. For example, soil from the Rhone Valley contains significant amounts of coarse aggregates and, if the builders of the past had wanted to manufacture adobes with this earth, they would have had to sift (or grind) it, which was not possible at that time. Thus, the technique best suited to this granularity of earth was rammed earth, which explains why almost all the earth buildings in the Rhône Valley are built using this technique.

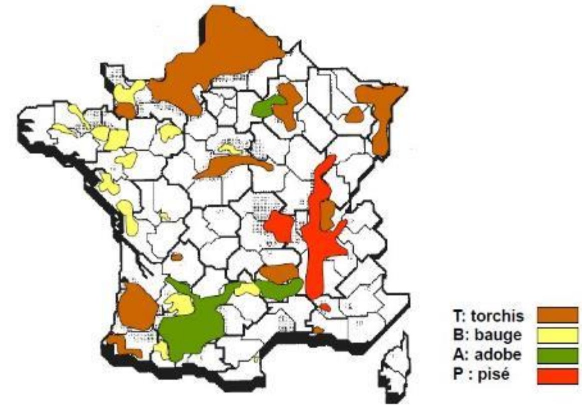

Figure 1. Geographical distribution of earthen heritage in France ("pisé" = "rammed earth", "bauge" = "cob", "torchis" = "wattle and daub") based on Guillaud (2018)

A similar analysis can be made for cob in Normandy but, this time, one of the reasons for the choice of this technique over others is not necessarily related to the characteristics of the earth but more to the meteorological conditions: although the earth from Normandy has a granularity usable for the manufacture of adobes, the humidity of the earth and the difficulties of drying it oriented the builders towards "adobe put directly in place without drying", namely cob. In cases where the earth used was too clayey, the high water contents caused significant cracking of the materials during drying: the masons of the past found a way to solve this problem by adding plant fibres to the mixture, which both limited cracking during drying and gave a better structure to the fresh pieces of cob. In the south-west, hot, dry summers coupled with the excellent properties of the soil from the Garonne Valley led to the development of adobes in this region.

Thus, the vernacular heritage shows us that builders learned by experience to adapt to local materials. The same was true for the formulation of the materials they used: they had no balance, no granulometric curve and even less chemistry or mineralogy! They selected formulas based on their experience, as some - but unfortunately too few - craftsmen still know how to do today.

Analysis of the built earth heritage is very useful for the development of modern earth materials. Since the arrival of concrete, there has been a significant loss of know-how and today's researchers must rediscover the secrets of earth materials, drawing inspiration from works of the past that have proved the effectiveness of the techniques and their durability. Pacheco-Torgal and Jalali tried to write a review, which had the attractive title "Earth construction: Lessons from the past for future eco-efficient construction" (Pacheco-Torgal and Jalali, 2012). However, the authors failed in their attempts, particularly as far as the place of stabilization in the built heritage was concerned (Morel et al., 2013) as, throughout the article, the authors seem to postulate that the stabilization technique (e.g., addition of hydraulic binders) is a compulsory step for earth construction. Yet this is not consistent with the authors' stated objective of linking traditional earth constructions to the modern use of earth as a building material: such traditional buildings are mostly structures made of unstabilized earth, even for areas subject to heavy rains (Northern Europe).

Numerous studies that have been published on heritage earth materials and the following references can be cited as examples for adobes (Adorni et al., 2013), (Aubert et al., 2015), (Cardiano et al., 2004), (Costi de Castrillo et al., 2017), (Fratini et al., 2011), (Pagliolico et al., 2010), (Quagliarini et al., 2010), (Uguryol et al., 2013) and (Wu et al., 2013). These references differ by the periods (from 2000 BC to the 19th century) and the countries studied (Italy, France, China ...) but they all have in common that no old adobe was stabilized. Examples of stabilization of earth materials in vernacular heritage are exceedingly rare and often only concern military fortifications, where some earth materials were stabilized with lime (cement did not exist at the time as it was discovered only in the 19th century). If there are lessons to be learned from the past for the production of modern earth materials (as suggested by Pacheco-Torgal and Jalali), it is important to focus on unstabilized earth materials. As mentioned earlier, the main weakness of earth used as a construction material is its sensitivity to water. Our earthen built cultural heritage, which has resisted the passage time even though the earth was not stabilized, is an illustration of the fact that the systematic use of stabilization for these materials is questionable. The builders of yesteryear were able to solve this problem thanks to their constructive intelligence. They developed a variety of strategies to protect earth constructions against water: orientation of the building and of its earth walls with respect to the dominant rain direction, advanced roof, impermeable foundations or, in some cases, protective lime coating.

3 NEED FOR NORMS

The world of building materials has changed and today it is necessary to talk about standards, control, performance and modelling. Although some international standards exist (in India, Nepal, New Zealand, Sri Lanka, the USA or Australia for example), the lack of standards and regulatory texts on earth construction is holding back the renewal of the use of this material in modern constructions, especially in Europe. In France, for example, the only standard that exists on these earth building materials is an old standard for Compressed Earth Bricks (CEB) (NF XP 13-901, 2001), which is no longer applicable and is currently being revised. There is nothing on other techniques. In Europe, the most advanced texts are in Germany, where, since 1999, there are regulations for earthen construction that cover the aspects relative to the implementation of earth materials on site: selection of soils, definition of testing procedures and definition of construction technologies. Following on from this, the German Standard Institute has recently set up 3 standards on earth construction products: one on earth bricks (DIN 18945, 2013), one on earth masonry mortars (DIN 18946, 2013), and one on earth plasters (DIN 18947, 2013).

It is very interesting to note that, in these three German standards, the addition of chemical or mineral stabilizers (e.g. lime or cement) is not allowed. Thus, stabilized bricks are not considered in the German standards. This specificity raises some questions and allows us to introduce the next part on the issue of the stabilization of earth materials. For comparison, brick stabilization was allowed in the old French standard on CEB and that will continue to be the case in the new version, which will cover not only CEB but all the techniques for making earth bricks (adobe, CEB and extruded bricks). Thus their taking account of stabilization will be an important difference between the future French standard and the current German ones.

4 QUESTIONS ABOUT STABILIZATION

Even though earth has many advantages, as presented in the introduction, the interest of using earth as an alternative to concrete lies mainly in the significant reduction of the environmental impact (embodied energy and CO_2 balance). However, the chemical stabilization of earth materials by mineral binders (sometimes lime but especially cement) is becoming more widespread, which raises the question of the relevance of the use of earth. The reasons for this stabilization are multiple. The main one is water resistance, even though we have seen that the built heritage shows that it is possible to do without it. The second reason is the mechanical performance gain, which will be discussed in the following part of this section. Another reason is related to the manufacturing conditions: in the case of rammed earth, the use of binders makes it possible to reduce the stripping times and, in the case of CEB, it facilitates the handling of the bricks in the short term. A more recent trend is to make earthen concrete to facilitate the use of earth materials, to use the same tools as for concrete, and to reduce the labour required for more traditional earth-based construction techniques.

Whatever the reason for the use of cement in earth materials, it is necessary for this addition to remain consistent with existing conventional products. If we consider the case of stabilized earth bricks, for example, these plain bricks are in competition with hollow concrete blocks. In the hollow concrete blocks, the cement content is about 150 kg/m^3 and the void percentage is 50%, which gives a cement mass of 1.5 kg per block for a conventional hollow concrete block (20cm x 20cm x 50cm). In a block having the same dimensions but composed of earth with a density of 2 t/m^3, the cement content equivalent to that of a hollow concrete block is 3.75%. This means that, if there is more than 4% stabilizer in an earth brick, the cement content becomes greater than that of a concrete block - whose performance in terms of durability and resistance are no longer to be demonstrated. Unfortunately, in most studies with stabilized earth bricks, the cement content used is higher than this value, which raises many questions.

Van Damme and Houben (2018) come to similar conclusions in their excellent paper entitled "Earth concrete. Stabilization revisited". The authors used simple tools to assess the environmental impact of OPC addition for the stabilization of earth materials, in particular by using the binder intensity index or the carbon intensity index introduced by Damineli et al. (2010). The authors' conclusions of the are the following: “Provided some simple architectural rules often inscribed in the local constructive culture are followed, construction with unstabilized subsoil is a durable technology that has a role to play in the formidable affordable housing challenge awaiting us in the coming decades. Our analysis just points to the fact that stabilization with OPC is, in most situations, not worth the effort, neither in mechanical nor in environmental terms. It brings only moderate mechanical improvement at a rather large environmental cost. Climate change may possibly modify the architectural rules to be followed, but rather than systematically and massively transforming earth into a low quality PC concrete, it would be more appropriate to adapt the architectural practice and/or to look for alternative and more environmentally sound stabilization methods”.

5 CONCLUSIONS

The renewal of earth construction is underway! And this renewal must not be allowed to forget all the lessons of the past, even if, with our modern tools, it should be possible to build even better and for longer than the builders of the past. But the road is still long and it is full of obstacles. Among them, we have seen that vigilance is needed concerning a reasoned use of cement as stabilizer. Much research is in course to look for alternative solutions to cement for the stabilization of earth materials, especially the use of biopolymers where, again, it is possible to draw inspiration from vernacular craft practices. The other challenge will be the development of the earth construction sector. This inevitably involves standardization of products but that is not all. It is necessary to bring together the various entities involved in construction (from the craftsman to the big building company, architects, design offices and researchers). This is currently the case in France, with a major national project on earth construction that will certainly begin in 2020. In addition, the training needs are also enormous because the know-how on these old materials has almost been lost and it is necessary to train new generations of builders with earth. Finally, research needs are also great and researchers around the world are beginning to structure themselves to work together to improve the properties of earth materials and to better understand their mechanical, hygrothermal and durability behaviour. This is one of the objectives of the Rilem TC "Testing and characterization of earth-based building materials and elements" which was set up in 2016 and whose research is ongoing.

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