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Vulnerability of earth material to water: A state of the art

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ABSTRACT: As the increasingly alarming observations on the state of our planet accumulate, a triple challenge - to provide decent housing for an increasing number of people, at low cost and with an extremely low environmental impact - leads us to consider a radical change in our constructive practices. In this perspective, raw earth, commonly perceived as outdated and marginal, meets a new interest. However, the material's sensitivity to water is commonly perceived as a barrier. Because earth, a material with a natural phase change, switches from a liquid to a solid state by simply varying its water status. By a three-step reading that distinguishes the traditional approach, the modern approach and finally the material approach, it appears first of all that, although the use of earth for building is very old, we have little knowledge from this long practice. The modern approach has made it possible, on the one hand, to inventory a heritage threatened with extinction and, on the other hand, to characterize the material, but without succeeding in explaining the origin of its cohesion. As for the responses to water, they do not seem satisfactory. The matter approach, by considering the earth as a clay concrete, finally makes it possible to understand the origin of the cohesion of the earth, thanks to important knowledge transfers coming from the study of colloidal dispersions and dry and unsaturated granular media. It then appears that water, far from being a threat to the durability of the material, is in fact intimately linked to the material. It ensures cohesion by the capillary forces it exerts within the grainy material and interacts with the clay to form a colloidal dispersion whose properties directly influence the characteristics of the material. Through this new understanding, the characterization of the material must be considered according to new criteria and the implementation of existing techniques as well as the development of new techniques are facilitated. However, considering that this new approach is relatively recent and that research on earth remains marginal, many areas of research remain open and need to be explored.

1 INTRODUCTION

In recent years, increasingly alarming statements about the state of our planet have been disseminated by many international institutions. Thus, in 2005, the Millennium Ecosystems Assessment (MEA, 2005), published at the initiative of the UN, stated that "over the past 50 years, humans have changed ecosystems more rapidly and extensively than in any comparable period of time in human history, largely to meet rapidly growing demands for food, fresh water, timber, fiber and fuel. This has resulted in a substantial and largely irreversible loss in the diversity of life on Earth". (IPCC, 2018) predicts an inevitable increase in average temperatures of 1.5°C due to human activities since the beginning of the industrial era. To avoid a more significant increase, considering that the consequences are exponential, global CO2 emissions must start to decline drastically from 2020 to reach net zero level by 2055 at the latest, best by 2040. Yet the construction industry and the housing stock are among the sectors of human activity that have a major impact on these issues.

The situation of humanity is also alarming. On the one hand, WHO held its first World Conference on Air Pollution and Health from 30/10/2018 to 01/11/2018 (WHO, 2018), after having noted that this pollution was responsible for nearly 7 million deaths/year. On the other hand, the world population now stands at 7.5 billion people, with an annual growth rate of 1.1%, or 83 million people. Projections by (United Nations, 2017) predict that this growth rate will slowly decrease to zero by 2100, when the world population reached 11.2 billion people. It seems very likely that the vast

majority of them will have to live in great economic fragility, considering the evolution of inequalities as described by the World Inequality Database (WID, 2018).

We are therefore faced with a triple challenge: to provide decent housing for an increasing number of people, at low cost and with an extremely low environmental impact. To answer this question, our constructive practices will have to change radically. Sustainable development no longer seems to be an option (Meadows, 2016). It is therefore at the very least a question of creating the conditions for resilience, to which even the World Bank calls (Hallegatte et al., 2017). To quote (Barrau, 2018), these profound changes are no longer the whims of a few ecological nutters because if this fight is lost, the others will no longer have any reason to be. It is therefore urgent that the reception of seriousness changes sides, the only madmen being those who, facing the precipice, urge us to accelerate towards more growth.

These changes seem to question the roots of our relationship to the world since, as pointed by (Servigne and Stevens, 2015) among many others, the state of our world forces us to see the harmfulness of the dominant socio-economic model. Yet this model is inseparable from the paradigm of Modernity which, distinguishing "by nature" the subject and the "extended thing", separated them and placed the world at the exclusive and unlimited service of mankind in a progressive and individualistic perspective (Morin, 2015). This vision of a human entity independent of the world around it is questioned by a number of studies that highlight not only that this distinction is a question of degree and not of nature(Cyrulnik, 1997), but also that it seems that we are permeable to the world, even to the very seat of our individuality, our brain (Roberts et al., 2018). The conditions therefore seem to be in place for the emergence of a new ontology reconciling humans and the world, "beyond Nature and Culture"(Descola, 2015).

In this perspective, earth (we will use *earth* in place of the more correct *raw earth* for the sake of simplicity), commonly perceived as outdated and marginal, meets a new interest. Indeed, this material is very abundant and very inexpensive, its life cycle has an exceptionally low environmental impact and its use is based on an understanding of "doing with" and not "doing against"(Ingold, 2013). We are therefore interested in earth, animated not by the question "Should we build with earth?" but rather by "How do we build with earth?"

As such, the material's sensitivity to water is commonly perceived as a barrier. Because earth, a material with a natural phase change, switches from a liquid to a solid state by simply varying its water status. This characteristic gives it both its qualities, since it can be shaped as desired during implementation and reused after demolition, and its vulnerability, since an earthen building can easily be damaged. A state of the art of the issue therefore seems necessary.

To do this, we will begin by briefly considering the history of the use and knowledge of the material by distinguishing two main periods, which we will refer to as "approaches"(Anger, 2011): the vernacular approach, corresponding to traditional practices and which began with the sedentarization of mankind around 10,000 BC and declined from the beginning of the industrial era; and the material approach (in the following, we will distinguish between matter and material, meaning matter as "what constitutes any body having a tangible reality", and material as "the matter used to make an object", i.e. "a basic matter selected because of particular properties and implemented for a specific use". The notion of utility distinguishes between the two and characterizes a descriptive and comprehensive approach as opposed to an interpretative and performative approach) which corresponds to modern practices and which begins with the emergence of modern sciences and takes off with industrialization. Although this extreme simplification is necessarily somewhat caricatural, it will allow us to better measure the contributions of a 3rd approach that has recently appeared, the matter approach, which corresponds to the recent renewed interest in earth material and is based on the latest advances in understanding the material. We will discuss this last approach in more detail, in that it profoundly renews the way we look at the relationship between earth and water. Finally, we will conclude with some considerations on research opportunities.

2 TRADITIONAL APPROACH

Before the industrial era, " architectures of places, not architectures of times" (Bret, 2018) prevailed, which were based on the use of locally available resources and specific building cultures. These architectures demonstrate remarkable intelligence in the intimate links they maintain with the places where they were built and the communities they house (Oliver, 2007).

As earth is an abundant and widely available resource, it is one of the oldest and most widely used materials by mankind for edification of its built environment. Indeed, the oldest traces of earthen buildings date back to the early Neolithic period (McCarter, 2012), some 10,000 years before our era, and are then found in the vast majority of inhabited areas of the globe. It is considered that even today, 1/3 of humanity still lives in an earthen habitat (Fontaine et al., 2009).

It has been used to build all types of buildings, from ordinary domestic architecture (Piesik, 2017) to the most remarkable (Stevens, 2015). Thus, "over 10% of the World Heritage properties incorporate earthen structures" (WHC, 2018).

This diversity is matched by a wide variety of construction techniques, which sometimes differ substantially, sometimes subtly. (Guillaud and Houben, 1989) propose a classification of substantial variations into a "wheel of techniques" divided into 12 types defined by the implementation modalities, including the so-called "modern" techniques, and into 3 categories defined by the nature of the work produced: masonry, monolith, and filling. It should be noted that some types group very different techniques, such as type 5 which groups rammed earth and blocks compressed manually or mechanically.

2.1 *Knowledge*

The knowledge we have about these traditional techniques comes mainly from relatively recent work and studies. Indeed, the transmission of this constructive knowledge used to be essentially based on an oral tradition. Therefore, we can only rarely rely on direct sources. For example, despite the intense use of earth in the Middle Ages in Europe, the available sources can provide us with information on supplies and labour requirements mainly through bookkeeping, but very rarely mention technical considerations (Bernardi, 2014). The buildings themselves are now the main witnesses, as are the few parts of the world where these practices are still alive. It is therefore necessary to refer to the work and studies most often related to archaeology or anthropology in order to have detailed knowledge.

2.2 *Water*

The subtle variations mentioned above mainly concern the multiple "recipes" of preparation using various additives to improve the employability of the material, its mechanical performance or its durability, among which and principally with regard to water. Many studies, including those on heritage, provide us with an extensive description of these recipes. Among many others, we can mention the use of seawater for earth preparation in Japan (Nakamatsu et al., 2017), the decoction of néré's pods or shea butter used in West Africa (Joffroy and Djanguenane, 2005), or the vegetable bitumen of pueblos from New Mexico(Coffman et al., 1990). (Vissac et al., 2017) presents an inventory of the main recipes, classified according to the nature of the additives used.

3 MODERN APPROACH

With the emergence of industrialization, the development of "architectures of times" (Bret, 2018) corresponds to the development of manufactured building materials, the production and implementation of which are part of a formalized process and based on technical and scientific knowledge providing extensive documentation. As earth is not part of these new developments, it will remain very little studied and documented. Books such as Cointeraux's "Ecole d'architecure rurale" (Baridon et al., 2016) are an exception.

As exposed by (Dethier, 2017), it was not until the second half of the 20th century that a new interest in this material developed, with the exception of a few scattered initiatives. It is the awareness of an endangered tangible and intangible heritage and the emergence of ecological thinking that will lead the "pioneers" to inventory and preserve the raw earth heritage on the one hand and to establish the technical standards for the implementation of the material on the other. The holding in 1972 of the 1st International Symposium on the Conservation of Raw Brick Monuments in Yazd, Iran, and the creation in Grenoble, France, of the CRATerre in 1979 are emblematic of this movement.

3.1 *Knowledge*

The heritage study established a wide knowledge of the techniques and achievements mentioned above. The technical study of the material has led to the establishment of different standards of earth construction (Maniatidis and Walker, 2003), the development of new implementation techniques such as light earth (Volhard, 2016) or Compressed Earth Block (CEB), and the mechanical and physical characterization of the material. On this subject, and as (Anger and Fontaine, 2005) explains, a limited number of works, around 200, have proposed a characterisation of the earth material according to the most common mechanical and physical properties (compressive strength, fire behaviour, hygrometric behaviour, thermal behaviour, etc.). Considering that nearly half of them concern CEB and the other half concern all the other techniques (adobe, rammed earth, wattle and daub, light earth, cob, plasters, mortars and others) and that the number of publications per property to be characterized is distributed, it is not rare to find less than 5 references per property. In addition, some reservations about methods and results may be expressed, which we will detail later. However, (Moevus et al., 2013) have prepared an exhaustive review of these results, and provides a clear summary view of the results.

3.2 *Water*

In either case, water is considered above all as a danger whose earthworks must be preserved. The most common responses to this danger are, on the one hand, conservation practices such as "shielding" (Odul, 1990) and, on the other hand, the use of cement stabilization, as evidenced by the various standards and regulations that result from this research (Maniatidis and Walker, 2003).

However, two observations lead us to reconsider these answers: "shielding" has in many cases caused the deterioration of the elements supposed to be protected; cement stabilization strongly deteriorates the environmental qualities of the soil, preventing its reusability on the one hand and increasing its Global Warming Potential (GWP) to a level close to that of cement concrete, or even higher if we consider the mechanical performances obtained according to the quantity of cement used (Van Damme and Houben, 2017).

4 MATTER APPROACH

For nearly 20 years, a change of approach has been taking place. The aim of this study is no longer to determine the constructive properties of the material, but to understand the behaviour of the matter, in order to answer the simple yet unexplored question of "How does it stand?", or, formulated differently, "how to explain the cohesion and decohesion of this phase-change material, i. e. that it passes from the liquid state to the solid state by simply varying its hydration rate"?

Initiated in 1996, the Terra Project (Van Damme et al., 2010) considers earth as a clay concrete, consisting of a granular skeleton and a cohesive matrix (Van Damme, 2013). This granular skeleton consists of pebbles (from 2 to 20cm), gravel (from 2 to 20mm), sand (from 60µm to 2mm) and silts (from 2 to 60µm), in variable proportions depending on the earth considered. The matrix is a colloidal dispersion composed of an aqueous solution and the finest fraction of the earth (<2µm), composed of mineralogical clays (hydrated phyllosilicates) and various particles such as metal oxides (Fe, Al), quartz fragments, more or less hydrated silicas and limestone crystals.

Based on recent advances in fields such as the physics of dry and wet granular media, or the study of colloids, the behaviour of earth can therefore be understood as developed by (Van Damme et al., 2010, Fontaine et al., 2009, Anger, 2011, Anger, 2005) by considering: a) the behaviour of a dry granular medium, which essentially depends on 3 criteria: the compactness of the stack, porosity and coordination ; b) the behaviour of a colloidal dispersion, which essentially depends on the interaction forces between the surface of the dispersed solid particles and the dispersion solution; c) a moist, or unsaturated, granular medium, which is characterized by the proportions between the different phases as well as by the specific characteristics of each of the phases: solid (grains), liquid (colloidal dispersion), and gas (air).

This approach has three major consequences: a) water, or more precisely the aqueous solution that constitutes the liquid phase, is a decisive element in the cohesion and structuring of earth; b) the physico-mechanical behaviour of the material should be considered according to new criteria, e. g. when using additives; c) the implementation of existing techniques and the development of new techniques is facilitated by knowledge and technology transfers.

4.1 *Water and cohesion*

As exposed by (Bui et al., 2014, Gerard et al., 2015), the variation in the earth's water status has a direct influence on its level of cohesion. Like a pile of sand whose angle of fall varies according to the quantity of water it contains, the behaviour of the unsaturated granular medium that constitutes the earth will vary according to the proportion between its different phases (Fontaine et al., 2009). But the nature of this liquid also matters. This liquid is not a homogeneous solution here, but a colloidal dispersion whose behaviour depends on the one hand on its degree of concentration and on the other hand on the interaction forces between the surfaces of the particles and the solution in which they are dispersed. The quantity and quality of water are therefore each decisive in the cohesion of the earth.

4.1.1 *Capillary water*

First, in an unsaturated granular medium, it is the capillary bridges created by the liquid phase between the solid grains that determine the degree of cohesion. Thus, between the plastic soil used to shape an adobe brick and the water-equilibrium brick, or dry brick, the proportion of water decreases from +/-25 % to +/-2% (Moevus et al., 2013) and the compressive strength, initially practically zero, can reach up to +/-2,5 MPa (Kouakou and Morel, 2009). Excess water causes the capillary bridges to fuse and reduces the cohesion of the material, just as the total absence of water causes the capillary bridges to disappear and thus disintegrate the soil. The aim is therefore to determine an optimum water content. Moreover, between a pile of loose earth and the same earth freshly rammed into a mud wall, the water level does not vary, but the cohesion of the earth is radically different. The reorganization caused by the ramming, by increasing the compactness and coordination of the earth, multiplies the capillary bridges and thus its cohesion.

From this point of view, earth naturally, although in a variable way depending on its composition, has several positive characteristics: a) the continuous distribution of the grains from the nanometer to the decimeter makes it possible to achieve a higher compactness and coordination than in a homogeneous granular medium whose compactness cannot exceed 74% (Anger, 2005); b) the attractive pressure within a capillary meniscus being inversely proportional to the radius of curvature of the meniscus, the smaller the grains, the stronger the cohesion, and earth contains a large quantity of extremely fine grains (Gras, 2011); c) some of these fine grains, clays, have the dual characteristic of being extremely hydrophilic and looking like "plates" or "leaves", between which the attractive forces are particularly strong when they are coplanar.

4.1.2 *Aqueous solution*

The arrangement of the clay sheets is therefore a determining factor in the cohesion of the soil. Referring to the Atterberg limits, the techniques for implementing earth can be distinguished by the water status of the mixture: wet (rammed earth, CEB), plastic (adobe, cob), liquid (plasters, mortars, poured earth, light earth) (Moevus et al., 2013). If the mechanical reorganization as carried out on wet earth has only a very marginal influence on the arrangement of the platelets, the situation is quite different when it is used in the plastic or liquid state. Indeed, under these conditions, there is enough water to allow the movement of particles in the colloidal dispersion. However, it appears that the pH of the aqueous solution and its content in ionic solutions have a strong influence on the flocculation and deflocculation of dispersed particles, and more particularly of metal oxides and clays. The level of (de)flocculation of the particles has a major influence on the rheology of the mixture and on the organization that the particles will adopt when the construction water is removed, determining the porosity and density of the material, and therefore its mechanical and physical properties (Moevus et al., 2016).

4.1.3 *Adsorbed water*

Clays have another particularity: they are extremely hydrophilic. However, this characteristic will vary significantly depending on the type of clay. The mineralogy of clays classifies them according to 3 criteria: the type of sheet defined by the molecular layers that compose it; the surface charge of these sheets; the nature of interleave spacing (Moore and Reynolds, 1989). Thus, illite will be described as a 2:1 clay (for 2 tetrahedral layers and one octahedral layer) /very high charge deficit (+/-1.6 charge per mesh) /highly bonded sheets without spacing. Depending on surface loads and interleaf spacing, a clay will have a greater or lesser tendency to adsorb water molecules. This adsorption causes the sheets to swell, and so desorption causes deflation.

This phenomenon plays a role on several levels (Moevus et al., 2013). During processing, swelling causes a change in the viscosity of the dispersion and therefore of the soil, while deflation causes the clay to shrink during drying and can therefore cause cracks in the material. Once the material has reached its hydric equilibrium, adsorption/desorption, combined with the porosity of the material, is a determining factor in the hygrometric regulation properties of earth.

4.2 *Material characterization*

As we have seen previously, the number of reference works on the characteristics of the material is limited. The situation is further complicated by the fact that, through ignorance of its cohesion mechanisms, earth has generally been considered a continuous material and that parameters such as the pH of the mixing water or the ambient humidity level are not systematically documented, let alone studied as to the impact of their variations on the behaviour of the material. It is therefore necessary to take the results of the majority of existing studies with caution, on the one hand, and to consider new studies taking these parameters into account, on the other hand. This work has been initiated, as by (Eid et al., 2015, Hamard et al., 2016, François et al., 2017).

Understanding the fine structure of the material and the behaviour of its various components allows us to better understand and implement the properties of the material. Thus, when the material has a high porosity, due to, among other things, a flocculated arrangement of the clay plates, it will absorb water more easily, which has a double effect: a) increasing its hygrometric regulation properties in the ambient air; b) making it more vulnerable in the event of exposure to liquid water. It is also interesting to note that during water exchanges between the earth and the ambient air, the water changes phase, thus contributing to the thermal regulation of the ambient air. By intervening on the mixing water and therefore on the arrangement of the clay plates, it is therefore possible to have a significant influence on these properties of the material. The study conducted by (Moevus et al., 2016) demonstrates the potential of this type of process.

Similarly, the study of the use of additives and traditional recipes becomes more precise by understanding the interactions between these additives and the structure of the material. (Vissac et al., 2017) lays the foundation for a better understanding of the action of biopolymers used in various traditional recipes. For example, the identification of the role of tannins present in the decoction of néré's pods makes it possible to consider the substitution of néré's pods by other sources of tannins in regions where these pods are not available.

4.3 *Technology transfers and new developments*

Research on the earth material was and remains marginal. By requalifying the material as clay concrete, the transfer of knowledge and technology from significantly more invested fields makes it possible to give a new dimension to research on this material. Thus, the control of granular stacks developed for high-performance concretes has made it possible, among other things, to develop new implementation techniques such as zero drop angle rammed earth (Le Tiec and Paccoud, 2006).

These transfers are strongly mobilized for one of the major current challenges of earth material: Self Compacting Clay Concrete or SCCC (Van Damme and Houben, 2017, Landrou et al., 2018). The aim here is to propose an implementation that is as close as possible to cement concrete. The first conclusive tests have already been carried out (Pointet et al., 2016). However, a problem persists: cement stabilization is still necessary to allow the formwork to be removed in a short time. In

order to eliminate the use of cement for the reasons explained above, current research is therefore focused on identifying additives with very low environmental impact and allowing rapid cohesion of the material while preserving its reversibility.

5 CONCLUSION

Progress in the knowledge of the earth material has made it possible to reconsider the role of water, which is no longer considered exclusively as a threat to earthen buildings, but also as an essential ally for the cohesion of the material. However, research on the subject is still extremely rare and concerns almost exclusively the implementation phase, for the development of new workability of the material such as SCCC. Although the first steps have been defined in some studies, much remains to be done on the influence of water on the finished material. The challenge here is to measure the reliability of the material during its life cycle in the face of the risks of excessive exposure to water.

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