Raw earth construction: is there a role for unsaturated soil mechanics ?

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ABSTRACT: “Raw earth” (“terre crue” in French) is an ancient building material consisting of a mixture of moist clay and sand which is compacted to a more or less high density depending on the chosen building technique. A raw earth structure could in fact be described as a “soil fill in the shape of a building”. Despite the very nature of this material, which makes it particularly suitable to a geotechnical analysis, raw earth construction has so far been the almost exclusive domain of structural engineers and still remains a niche market in current building practice. A multitude of manufacturing techniques have already been developed over the centuries but, recently, this construction method has attracted fresh interest due to its eco-friendly characteristics and the potential savings of embodied, operational and end-of-life energy that it can offer during the life cycle of a structure. This paper starts by introducing the advantages of raw earth over other conventional building materials followed by a description of modern earthen construction techniques. The largest part of the manuscript is devoted to the presentation of recent studies about the hydro-mechanical properties of earthen materials and their dependency on suction, water content, particle size distribution and relative humidity.

1 DEFINITION OF EARTHEN CONSTRUCTION

“Raw earth” (“terre crue” in French) is a building material consisting of compacted moist soil (clayey sand), with the possible addition of reinforcing agents such as fibres or chemical binders. Unlike “cooked earth” (e.g. conventional masonry bricks), the soil-water mix is subjected to the least possible transformations and is used in a form very close to its natural state.

Several construction techniques making use of raw earth have been developed over the centuries. These techniques adopt different manufacturing processes and are known under different names but all of them use moist soil as the base construction material.

The strength, stiffness and durability of raw earth are primarily governed by the inter-granular bonding generated by soil water capillarity. Fibres and chemical binders, such as lime or cement, may also be added to the soil mix to enhance mechanical properties. If lime or cement are used (typically in the proportion of 6% in weight), the term “stabilized raw earth” is employed to mark a difference with respect to standard raw earth that does not make use of chemical binders.

A raw earth structure therefore consists of compacted moist soil and may be described in geotechnical terms as a “soil fill in the shape of a building”. Depending on the initial moisture content and manufacturing process, the dry density and degree of saturation of a raw earth structure can be more or less high. In general, the degree of saturation is highest at the time of construction but rapidly drops due to the combined effects of solar radiation, temperature and relative humidity.

Because of the nature of earthen structures, geotechnical principles should be employed for their analysis and design. This is, however, seldom the case and the wealth of knowledge accumulated over the years about soil behaviour and, more specifically, about unsaturated soil behaviour has been little exploited so far by designers of earthen structures.

Earthen buildings are still conceived by resorting to empirical rules rather than engineering science. Yet, it is indubitable that a transfer of knowledge from geotechnical engineering to raw earth construction would greatly benefit the development of this building technique.

2 RECENT RENAISSANCE OF EARTHEN CONSTRUCTION

Figure 1 shows the energy consumption of the building, transport and industry sectors in Europe, the US and Japan as estimated by the OECD (2003). In Figure 1, only the energy for the operation of dwellings is attributed to the building sector while the energy used for the transportation of building materials to the site and the energy required for the construction and demolition of the structure are included under the transport and industry headings, respectively. This means that the total energy consumed by all activities related to building is even greater than that shown in Figure 1. In a recent publication, Szalay (2007) arrived to similar conclusions as those shown in Figure 1 and estimated that the operation of residential buildings is responsible for about 40% of all energy consumed in Europe.

The building sector is also the largest consumer of raw minerals and produces about 33% of the waste annually generated in the European Union (EEA 2010). This waste is usually not recyclable and is disposed in landfills, resulting in loss of land, pollution and social alienation.

From the 1970s, researchers started to quantify the environmental costs of construction. These studies were at the origin of a renewed interest in alternative construction materials with more eco-friendly characteristics than concrete and steel. Earthen materials appeared as a viable option because earth is harmless to human beings and can be easily sourced in the vicinity of the construction site with consequent reduction of transportation costs. Earth is also recyclable, and therefore inexhaustible, and when properly manufactured can offer high strength, excellent thermal properties and low embodied energy while remaining a low-cost material. The use of earthen materials can therefore reduce consumption of natural resources not only during construction but also during the life of a structure by cutting heating/air conditioning bills and by recycling demolition waste.

The advantages of earth as a building material have been known for centuries as demonstrated by the number of historical earthen structures worldwide; however, these advantages have started to be quantified only recently and are summarized below:

1 *Reduction of embodied energy*. The preparation, transportation and construction of earthen materials require only 1% of the energy needed for cement based materials. Similarly, the manufacture of compressed earth blocks requires, at most, one third of the energy of fired bricks, namely 440 kWh/m^3 compared to 1300 kWh/m^3 (Little & Morton 2001).

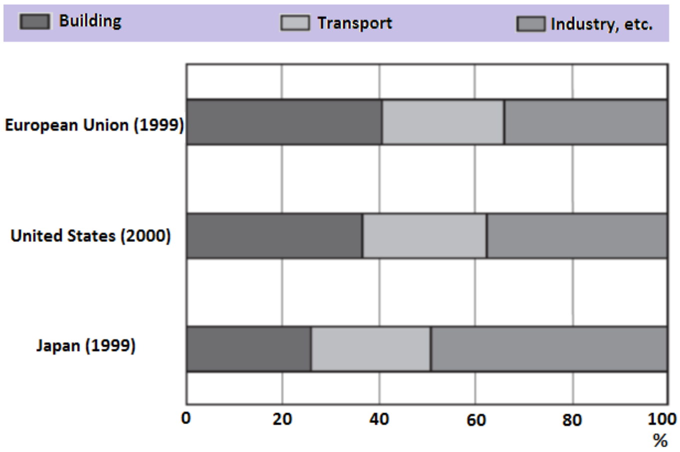


Figure 1. Energy consumption by sectors. Source: European Commission, US Department of Energy, Japanese Resource and Energy Agency (OECD 2003).

2 *Reduction of operational energy (hygro-regulator effect).* In a wet atmosphere, an earthen wall absorbs vapour due to the presence of clay in the earth mix. The absorbed vapour is released again when the surrounding environment becomes drier. This helps controlling the hygroscopic conditions inside a closed environment by absorbing excess moisture, storing it and returning it when necessary and, therefore, reduces the need for air conditioning to regulate relative humidity.

3 *Reduction of operational energy (thermo-regulator effect).* The hygro-regulator effect described at point 2 has also a significant role in controlling temperature inside dwellings. This is because water evaporation from the earth mass is an endothermic process that takes away heat (i.e. latent heat of evaporation) from the surrounding atmosphere during the hottest hours of the day; while water condensation inside the earth mass is an exothermic process that releases heat (i.e. latent heat of condensation) during the coolest hours. With respect to thermal properties, the conductivity of raw earth is relatively high and of the order of 10^{-1} W/mK while most insulating construction materials have conductivities of the order of 10^{-2} W/mK. The volumetric thermal capacity of earthen materials is of the same order of magnitude as that of concrete, i.e. around 2×10^3 kJ/m^{3}K (Houben & Guillaud 2006). However, the volume of an earthen wall is considerably larger than that of a concrete frame. This confers to earthen structures a greater ability to store heat during hot times and return it during cold times with a daily phase shift of 10-12 hours.

4 *Recycling or disposal of demolition waste.* According to Bossink & Brouwers (1996), the waste generated by construction and demolition of structures accounts for between 13% and 30% of all solid landfill waste world-wide. Of this amount, demolition waste represents the largest share, with an estimated ratio of demolition to construction waste of about 2:1 (Bossink et al.

1996). In this respect, waste from the demolition of earthen structures consists of plain earth that does not need to be disposed in landfills but can be easily recycled or safely released into the environment. However, this advantage is partly lost if chemical binders are used, in which case the eco-friendly credentials of raw earth are compromised and disposal of demolition waste into the environment becomes more problematic.

5 *Acoustic insulation.* Raw earth presents excellent acoustic characteristics and provides good sound insulation due to its high dry density (often in excess of 2000 kg/m^3) and thickness (often in excess of 0.25 m). According to the British Standard 8233 (1999), the sound reduction index R (in dB) of an ordinary masonry wall depends on its dry density, ρ (in kg/m^3) and thickness, t (in m) according to the following empirical equation:

$$R = 21.65 \log(\rho\, t) - 2.3 \qquad (1)$$

Equation 1 predicts that an earthen wall with thickness of 0.30 m and dry density of 2100 kg/m^3 has a sound reduction index of 58.3 dB, which is above the requirement of most building regulations. As an example, the Building Regulations by HM Government (2010) in the UK specify that “laboratory values of the sound reduction index for new internal walls and floors within dwelling-houses, flats and rooms for residential purposes, whether purpose built or formed by material change of use” should be at least 40 dB.

3 MODERN EARTHEN CONSTRUCTION

The main difference between modern and ancient earthen construction is given by the current availability of powerful machinery, which has reduced manufacturing times and has cut financial costs compared to the past. Design principles have instead remained almost unchanged for centuries, which highlights the need for new research, at the interface between structural and geotechnical engineering, to improve current methods of analysis. Among all modern techniques of earthen construction, the following ones are most common:

1 *Rammed earth.* Modern rammed earth uses the same material as ancient rammed earth (i.e. a mixture of soil, water and, sometimes, reinforcing vegetal fibres) but employs a more efficient construction process than in the past. Manual compaction with ramming poles is replaced by mechanical vibro-compaction with pneumatic rammers or plate compactors. This reduces construction times and achieves greater densification of the soil together with better quality control of the end product. Formworks are larger and lighter than in the past in order to facilitate assembly and dismantling, but also stronger to resist vibrations from tougher ramming. The movable small shutters of the past have been replaced by rolling or sliding modular formworks, similar to those employed in concrete construction.

2 *Prefabricated rammed earth.* Building of rammed earth structures often requires continuous assembly and stripping of formworks. When this is not possible, larger prefabricated rammed earth panels can be used instead. Prefabricated panels are produced on-site or off-site by compaction of a wet soil mix into formworks of variable shapes and sizes, e.g. a panel can be up to 2.5 m height, 500 mm tick and can weigh up to 7000 kg. After stripping of the formworks, panels are left to dry until the time when they are installed with the help of cranes usually on a bed of lime. Panels are manufactured in advance of building operations and it is therefore not necessary to wait long drying times between consecutive lifts of a wall. Prefabricated panels retain the main advantages of rammed earth construction, including architectural flexibility, while reducing labour costs and construction times and allowing better quality control.

3 *Compressed earth blocks.* Compressed earth blocks are manufactured, generally on site, by compaction of moist soil to a very high density inside rectangular cuboid moulds. Compaction is performed by means of hydraulic or mechanical presses that apply pressures between 2MPa and 15MPa. Powerful electrical or diesel-powered presses are often used, though lever-action manual presses also exist. Blocks are assembled in masonry structures without mortar but inserting instead a thin joint of mud slurry to compensate for surface roughness and enhance airtightness. Another potential application of compressed earth blocks (perhaps of larger sizes) may also be envisaged for the construction of geotechnical infrastructures such as embankments, dikes, dams and retaining walls.

4 *Casted earth (“Terre coulée” in French).* Casted earth is a novel technique developed by the laboratory CRATerre-ENSAG in France for the construction of non-structural walls. The technique makes use of an “earthen concrete” where aggregates are bound by clay rather than cement. In order to achieve good mechanical properties, suitable proportions of the different soil components (gravel, sand and clay) must be employed. If these proportions are not available on site, they must be sourced further away. Similar to traditional concrete, earth and water are blended inside a mixer and subsequently poured between formworks. This fluid earth mix must be consistent enough to minimize the thrust exerted on formworks during pouring. Casted earth walls are considerably faster to build than rammed earth walls given that it

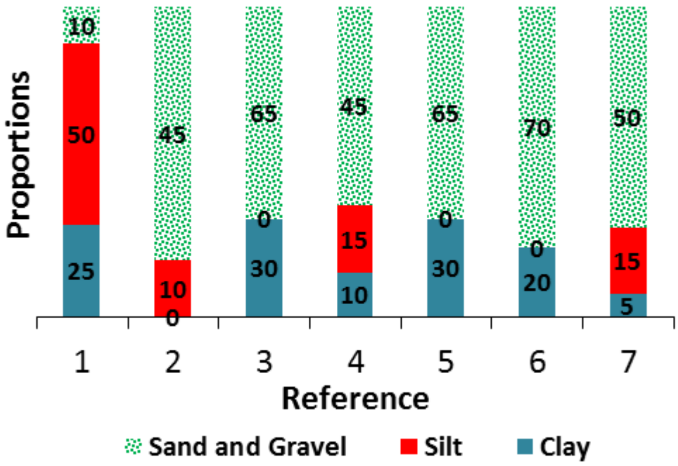
is much quicker to pour fluid earth between formworks than tamping damp earth in layers.

4 ROLE OF UNSATURATED SOIL MECHANICS

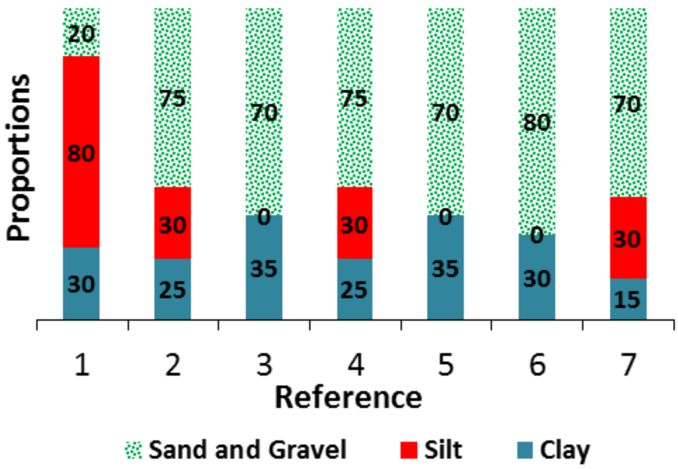
It is well known that unsaturated soils become stiffer, stronger and less permeable to water as suction increases and degree of saturation decreases. It is also well acknowledged that, when suction decreases and degree of saturation increases, unsaturated soils undergo either irreversible compression or reversible swelling depending on density and stress levels. Over the past 50 years, geotechnical engineers have developed accurate predictive models of these aspects of soil behaviour, which are also very relevant to raw earth construction. Unfortunately, for reasons that will be explained later, these models have never found application to the analysis of earthen structures, which are still designed as a "weak masonry" rather than being regarded as a porous continuum. Recent evidence has, however, started to question this design approach. For example, Langenbach (2004) studied the damages caused by the 2003 earthquake in Bam (Iran) and concluded that the failure of earthen structures was due to loss of cohesion, which is better explained in terms of porous continuum mechanics than discrete masonry models.

Stiffness and strength are key parameters during the analysis of construction, service life and failure of earthen structures; yet, very little research has been performed on the dependency of these properties on suction, water content, density and particle size distribution. Of course, geotechnical researchers have extensively studied the role of suction and water content in defining the engineering properties of partially saturated soils; however, the results from these studies are not directly applicable to the design of earthen structures because of differences in density and particle size distribution. Geotechnical research has in fact focused on unsaturated clay materials whereas raw earth structures are characterized by the presence of a significant silty-sandy fraction. For example, Figures 2a and 2b show the lower and upper values, respectively, of the different soil fractions in a typical earthen material, as reported by different authors.

Particle size distribution can have a marked effect on the mechanical properties of compacted earth. Wu et al. (2012) studied the effect of grain size distribution on compressive strength by mixing a natural soil (clay-silt 88.59% and sand 11.41%) with sand (sand 74.7% and gravel 25.3 %) in four different proportions of 1:0.6, 1:0.8, 1:1 and 1:1.2 by weight. This resulted in four different earth mixes with sand fractions varying from 60% to 45% by weight, and hence finer clay-silt fractions ranging from 40% to 55%. Note that Wu et al (2012) did not measure the percentages of clay and silt in the finer fraction. Specimens from these four earth mixes were lightly compacted at a water content of 19.5% into cuboid moulds of 200×90×50 mm and subjected to unconfined compression to measure the effect of particle grading on stiffness and strength. Inspection of Figure 3 shows that both compressive strength and stiffness increase when the clay-silt content increases from 40% to 49% but then decrease when it further increases from 49% to 55%.



(a)



(b)

Figure 2. Lower values (a) and upper values (b) of soil fractions in earthen materials according to: 1) Alley (1948); 2) Houben and Guillaud (1994); 3) McHenry (1984); 4) Norton (1997); 5) Radonovic (1996); 6) Schrader (1981); 7) SAZS 724 (2001) (after Walker & Maniatidis 2003).

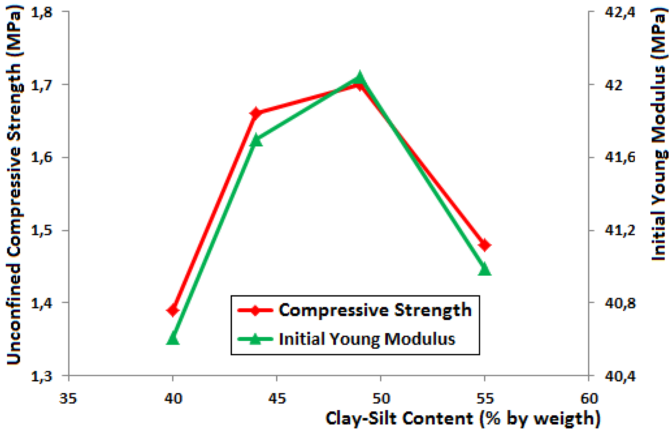


Figure 3. Stiffness and strength of earth mixes with different clay-silt fractions (after Wu et al. 2012).

Jaquin et al. (2009) studied the effect of suction and water content on the strength and stiffness of earthen materials. They performed a series of unconfined triaxial compression tests on samples dried to different levels of suction. The samples were axially compressed at constant water content while suction was measured by means of high capacity tensiometers mounted on the sample surface. Inspection of Figures 4 and 5 confirms that the strength and stiffness grow with increasing suction and decreasing water content. Conversely, the ductility of the material drops significantly with increasing suction and decreasing water content.

Suction tends to increase with axial strain for the specimens characterised by a high value of water content while tends to decrease for specimens with a low value of water content (Fig. 6). The results also suggest the existence of a retention curve relating water content to suction at critical state.

The influence of the grain size distribution on soil-water retention properties has been studied by Jaquin et al. (2008). They performed filter paper tests on two different earthen materials, mix A and mix B, both obtained by modification of a base soil used for a rammed earth development at Aykley Heads, Durham (UK). The base soil consisted of coarse aggregate, alluvial sand (dug from the construction site) and clay-silt, with proportions of 0.25: 0.60: 0.15, respectively. The optimum water content was determined from a compaction curve by using a vibrating hammer (British Standard 1377:2 1990) in order to reproduce the same material fabric of rammed earth and was found to lie in the range 8-10%. Jaquin et al. (2008) produced two different materials from the base soil by adding an extra 10% sand, in the case of mix A, and extra 10% clay, in the case of mix B. These mixes were statically compacted in layers at a water content of 10% in order to obtain samples with a dry density of 2.05 Mg/m^3, a value representative of modern rammed earth materials.

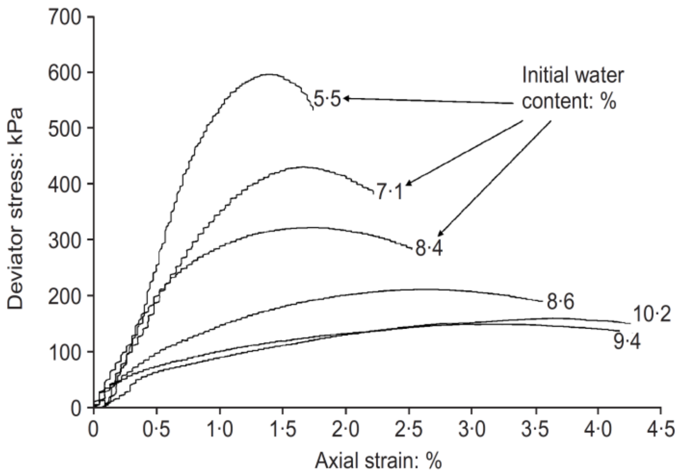


Figure 4. Triaxial tests at constant water content: deviator stress vs axial strain (Jaquin et al. 2009).

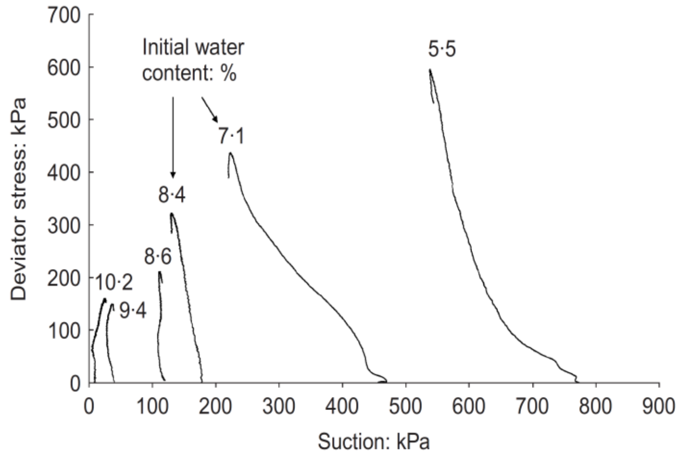


Figure 5. Triaxial tests at constant water content: deviator stress vs suction (Jaquin et al. 2009).

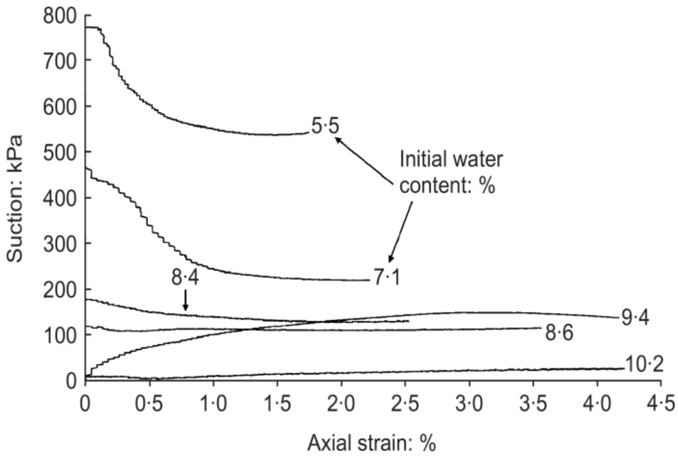


Figure 6. Triaxial tests at constant water content: suction vs axial strain (Jaquin et al. 2009).

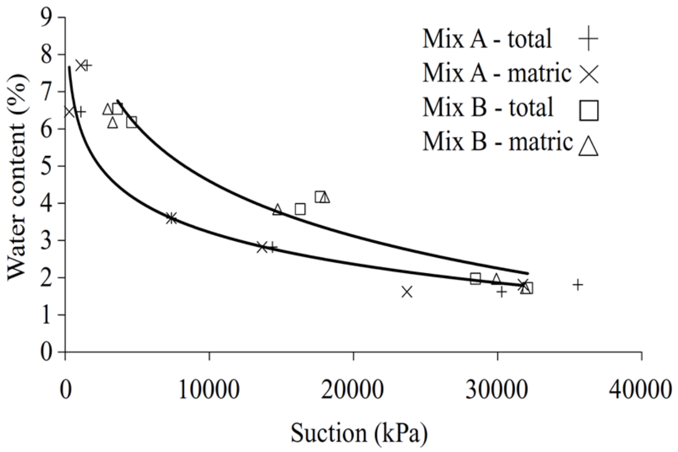


Figure 7. Drying curves for compacted earth mixes A and B (Jaquin et al. 2008)

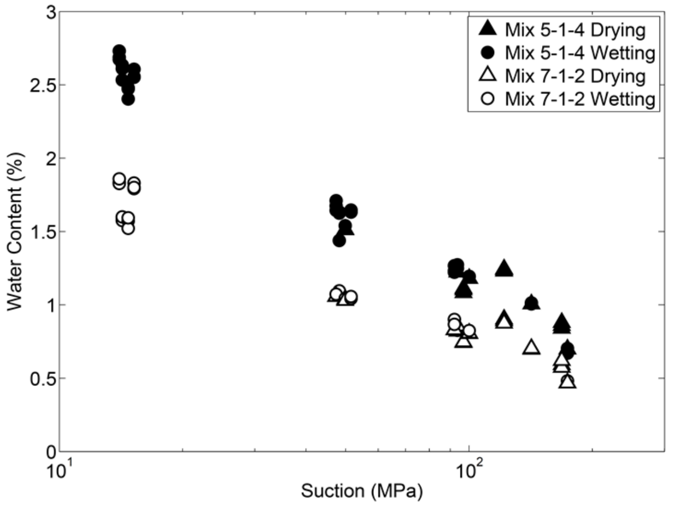


Figure 8. Drying and wetting data for compacted earth mixes 5-1-4 and 7-1-2 (Beckett & Augarde 2012).

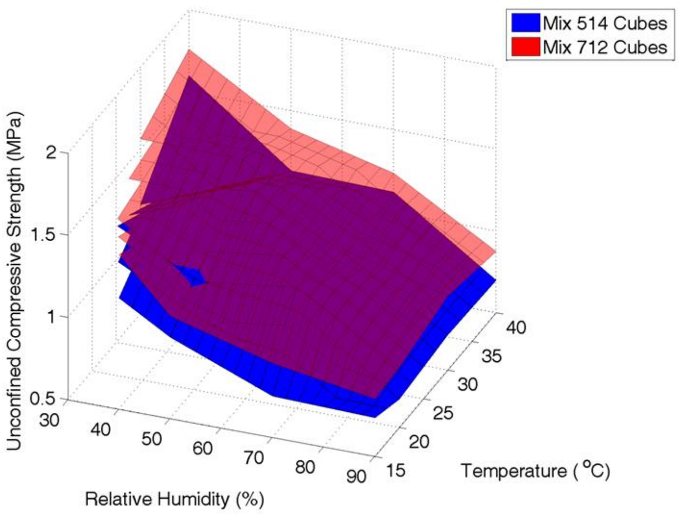


Figure 9. Unconfined compressive strengths for compacted earth mixes 5-1-4 and 7-1-2 (Beckett & Augarde 2012).

Figure 7 shows the drying curves of samples A and B in terms of both matric and total suction. Inspection of Figure 7 indicates that the osmotic component of suction is negligible (i.e. total suction and matric suction data seem to follow the same curve) and the curve of the coarser mix A is positioned below the curve of the finer mix B.

A similar study was performed by Beckett & Augarde (2012) who tested two different soil mixes. The first mix consisted of 50% sand, 10% gravel and 40% clay (mix 5-1-4) while the second one consisted of 70% sand, 10% gravel and 20% clay (mix 7-1-2). The two mixes contained the maximum and minimum recommended clay contents according to Houben & Guillaud (1996). In both cases, the gravel content corresponded to the minimum value recommended by Houben & Guillaud (1996). Samples were prepared by static compaction in layers at the optimum water content of 12%, to obtain dry densities between 1918 kg/m^3 and 1947 kg/m^3. The optimum water content was determined according to the light Proctor method and was approximately the same for both mixes. The results of the water retention tests are shown in Figure 8, which indicates that the coarser 7-1-2 mix presents lower values of water content than the finer 5-1-4 mix at the same suction.

Both investigations by Jaquin et al. (2008) and Beckett & Augarde (2012) conclude that a finer earthen material retains more water than a coarser one at the same value of suction. Given that finer and coarser samples were compacted to similar values of dry densities, this difference must be due to the pore size distribution rather than the total pore volume. The larger amount of smaller pores in the finer samples enables the retention of a greater volume of water at high suction levels.

Beckett & Augarde (2012) also investigated the unconfined compressive strength of 5-1-4 and 7-1-2 mixes by testing samples equalized at different values of temperature and relative humidity (15, 20, 30 and 40 °C and 30, 50, 70 and 90%). This experimental programme intended to replicate the prevailing climatic conditions in different regions of the world. Figure 9 shows that the samples with lower clay contents achieve higher unconfined compressive strength, a behaviour that was consistently observed for all humidity and temperature levels. On the basis of these results, Beckett & Augarde (2012) concluded that "the use of lower clay content materials should be considered for rammed earth construction in order to provide sufficiently strong materials in more humid conditions".

Compared to traditional geotechnical structures (e.g. dams, embankments), an earthen wall is characterized by a relatively large surface/volume ratio. Moreover, the presence of both internal and external surfaces generates higher gradients of temperature, relative humidity and suction across the earth mass compared to a geotechnical structure. Despite its relevance, only a handful of studies have however investigated the effect of environmental conditions on the hydro-mechanical behaviour of earthen walls. In addition to the already mentioned study by Beckett & Augarde (2012), another important contribution in this respect was made by Dierks & Ziegert (2002), who found that the compressive strength of earthen materials is notably reduced as the humidity of the surrounding air increases (Fig. 10).

For the material tested by Dierks & Ziegert (2002), the compressive strength reduces from about 5,7 MPa, at a humidity of 5%, to about 2,3 MPa, at a humidity of 95%. This is explained by the fact that, as environmental humidity increases, the water vapour condensates inside the earthen material causing the water content to increase and, hence, suction to decrease. The design of an earthen structure must therefore take into account the climatic conditions of the area where the structure is going to be built. Beckett & Augarde (2012) also commented that "structures should be designed based on both current and likely future climatic conditions".

Finally, another important factor governing the behaviour of raw earth buildings is the nature of the clay fraction. Different crystal structures and chemical properties of the clay fraction may induce different responses of the structure to mechanical or environmental actions. For example, two-layers clays such as kaolinite are characterised by a relatively low specific surface (10 m^2/g). These clays are weak binders of the coarse fraction and do not produce large swelling or shrinkage during wetting or drying. Conversely, three-layers clays are characterised by a large specific surface (1000 m^2/g) and can be divided into swelling clays (Micas and Illite) and non-swelling clays (Smectite). Generally, three-layers clays are stronger binders than two-layers clays because of their ability to attain higher values of suction at the same water content. However, when cement is added to the mix (i.e. in stabilized raw earth), the binding properties of swelling three-layers clays can be greatly reduced. For example, Fernandes et al. (2007) showed that, for a montmorillonite, sand and cement mix, a large amount of water is needed to ensure good workability. This in turn generates significant swelling of the montmorillonite fraction, which results in a relatively large porosity and, consequently, in a reduction of strength.

Although clay type is often dictated by local availability, it is still essential to have a good knowledge of the clay characteristics in order to decide the best destination of use of the earthen material. For example, earthen materials employed in non-structural elements (e.g. coating surfaces) must show low shrinkage/swelling in order to avoid cracking, so two-layers clay are normally preferred for these applications. Conversely, for structural elements (e.g. walls), three-layers non-swelling clays with powerful binder properties are favoured.

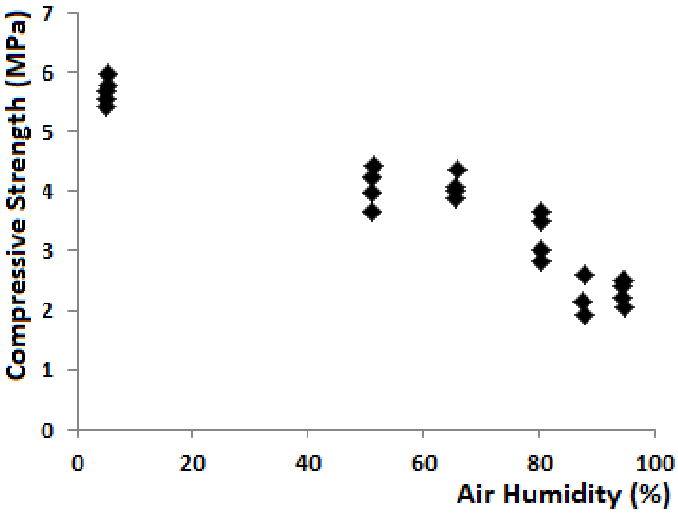


Figure 10. Variation of unconfined compressive strengths with air humidity (after Dierks & Ziegert 2002).

If locally available clays do not have the required mechanical properties, natural fibres (straw, flax, hemp and cellulose) can be added in suitable proportions to improve binding and/or to reduce swelling/shrinkage while preserving the low environmental impact (Röhlen & Ziegert 2013).

5 CONCLUSIONS

Until very recently, earthen construction was mainly seen as the domain of "green" enthusiasts or engineering researchers and occupied a niche market in the building industry. However, increasing evidence about the environmental impacts of natural exploitation and waste disposal associated to current construction practices is rapidly changing this perception. Engineers are now looking at earthen construction as a possible alternative for reducing the current levels of embodied, operational and end-of-life energy in the building sector.

The advantages of earthen construction have been known for millennia as demonstrated by the number of historical earthen structures that are still standing. Nevertheless, only in the last couple of decades the availability of powerful machinery for screening, mixing and compacting soils, and of efficient formworks systems that can be quickly assembled and dismantled, has made this construction technique viable at a large scale. Rammed earth, prefabricated earthen panels, compressed earth blocks and casted earth are some of the most popular techniques of modern earthen construction.

There is also potential for extending some of these construction techniques beyond the domain of residential building. For example, geotechnical structures such as dikes, dams, retaining walls and embankments could be built by means of large-sized compressed earth blocks, with potential savings of time and material compared to current practice.

Geotechnical principles are rarely used in the analysis of earthen structures, which are still designed by resorting to empirical rules rather than engineering science. Yet, the very nature of earthen materials makes them susceptible to the application of soil mechanics theories and, more specifically, to the application of unsaturated soil mechanics theories given that all earthen materials exist in an unsaturated state.

The development of raw earth construction would significantly benefit from a transfer of knowledge from geotechnical engineering. Unfortunately, the results from past geotechnical research on unsaturated soils cannot be directly translated to earthen materials because of differences in density and grain size distribution. This has meant that, during the past ten years, an increasing number of studies have been specifically targeted to raw earth materials. These studies have adopted many of the experimental procedures, interpretation methods and analytical models used in geotechnical research. This paper has reviewed some of these studies highlighting how earthen materials show similar trends of behaviour to the unsaturated soils investigated by geotechnical engineers. These studies validate the applicability of soil mechanics theories to raw earth construction confirming, once again, that an earthen structure might indeed be regarded as a soil fill in the shape of a building.

6 ACKNOWLEDGEMENTS

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