10. CONCLUSIONS

In this research, the prototype model proved to have seismic-resistant behavior against the dynamics of the earthquake simulator. Not only was collapse averted in the final state of the model, but also in the case of a real house, only a modest repair would be necessary to re-endow the structure with adequate strength. In addition, the construction system was easy to implement as demonstrated by the erection of the model, in which the workers executed the procedure without major difficulty, thereby also providing the possibility of self-reliant and rapid construction after a disaster occurs.

However, the production of adobe pieces compatible with the structure was required, along with partial reinforcement with geogrid mesh. In any case, the total surface assembly can prevent cracks from occurring, provided that a true bond is created between the dissimilar materials, earth and steel. This constitutes, therefore, a future line of research. Finally, the construction system resembles the building tradition of half-timbering, which also provides a basis of repair for the architectural heritage of adobe.

Fig.5 Detachments and cracks of the geogrid-reinforced plaster coating on the side perpendicular to the direction of the earthquake-movement simulation, after the fourth phase (displacement of 130 mm) (credits: Adell, 2008)

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HYGRO-THERMO-MECHANICAL PROPERTIES OF EARTHEN MATERIALS FOR CONSTRUCTION: A LITERATURE REVIEW

Mariette Moevus, Romain Anger, Laetitia Fontaine

Theme 6: Research in Materials and Technology for Conservation and Contemporary Architecture
Keywords: Earthen materials, hygro-thermal properties, mechanical properties, literature review

Abstract

Although earth has been used in construction for millennia and is still one of the most widely used building materials in the world, it is difficult to find reliable values of hygro-thermal and mechanical properties of earthen materials. Little scientific research has been conducted on this material compared to the huge amount of literature available for cementitious materials. Considering the literature on earthen materials, a majority of studies deal with cement stabilized earth for compressed-earth blocks or rammed earth. Less has been done about natural unstabilized earth.

The only existing comprehensive overview on the properties of earthen materials was authored by CRAterre-ENSAG and published 25 years ago. For the second time in its 30 years of existence, CRAterre-ENSAG has undertaken the task of re-actualizing this synthetic knowledge by writing a comprehensive review of the existing literature on the subject.

In the present work, we intend to compile the most reliable experimental data on hygro-thermal and mechanical properties of natural earth. We will inventory the performances determined by several research teams for rammed earth, compressed-earth blocks, adobe, cob and mortar. We will discuss the reliability of the experimental techniques used. We will provide an overview on the state of knowledge concerning the different properties, as well as on the lacking data. Finally, this literature review will also give some orientation for further scientific research.

1. INTRODUCTION

Building with earth requires that artisans have a very good knowledge of the material. Yet, there is limited scientific knowledge of the material. While builders develop their knowledge in the field through direct experience, engineering-consulting firms are hampered by a lack of reliable data regarding the properties of earth. Norms and standards are few, partial and often deal with compressed-earth blocks (CEB) stabilized with cement. However, there are many other reliable construction techniques involving earth that do not require the use of mineral stabilizers, as demonstrated through centuries-old examples such as the buildings, mosques and skyscrapers in the towns of Ghadames (Libya) and Shibam (Yemen), some sections of the Great Wall of China, the tulous – large residential complexes of the Hakka in China, or more locally, the many farms built with earth around the Rhône-Alpes region in France (Fontaine and Anger, 2009). These examples show that earth can be used for the construction of sustainable buildings.

This report is an update on the knowledge available on the hygrometric, mechanical, and thermal properties of earth. It deals mainly with the intrinsic properties of the material. This update is an opportunity make an inventory of knowledge and highlight the technical data gaps that could be usefully filled. Documents and information were gathered through CRAterre's Documentation Centre and scientific journals. Only results for which the materials and experimental protocols are described at least briefly have been included; this significantly reduced the number of documents that were used in this survey. In addition, we were interested in non-stabilized earth exclusively, which disqualified a great portion of the scientific data available.

2. DRY DENSITY

The dry density of soil is the ratio between its mass and its volume measured in the dry state, after oven drying at 105°C. This property depends on several parameters, dealing mainly with grain-size distribution, the volume and nature of the binding phase, the water content involved in the implementation of the earthen materials, and the energy involved in compaction of earthen materials compacted for building purposes.

Based on the values found through different documentary sources, we propose to distinguish between two families of techniques for the implementation of earth, leading to different properties of the earth material when dry: implementation by compaction (rammed-earth, CEBs) or plastic-state implementation (adobe, wattle and daub, cob). To these two families, a third category can be added, involving the addition of a high proportion of plant fibers (straw, hemp) into the earth mix, which leads to lighter materials. Table 1 gives typical ranges of variation of the clay content, plasticity index, initial water content, and dry density for these three families (Azeredo, 2005; CSTB, 2007; Bahar, 2004; Barras, 2010; Bui, 2008; Degirmenci, 2008; Goodhew et al., 2000; Goodhew and Griffiths, 2005, Heath et al., 2009, Kleespies, 1994, Laurent et al., 1984, Laurent, 1987; Mueller and Simon, 2002; Vega et al., 2011; Morel et al., 2003; Ola, 1987; Hakimi et al., 1996; Hall and Djerbib, 2004; Jaquin et al., 2009; Kouakou and Morel, 2009; Maniatidis, 2008; Olivier, 1994; P'kla et al., 2003).

Technique	Clay content (%)	Plasticity Index (%)	Initial water content (%)	Dry density (kg/m3)
Compaction	5 - 30	5 - 30	5 - 15	1600 - 2200
Plastic moulding	20 - 40	15 - 35	15 - 35	1200 - 2100
With added fibres				300 - 1200

Table 1. Typical values of dry density for earthen materials (credits: author)

3. HYGROMETRIC PROPERTIES

3.1 Water content

The water content of earth is a parameter of prime importance if we are interested in the mechanical and thermal properties of the material, so it is important to know the normal water-content range of earth in ambient humidity. The water content of soil at equilibrium is higher if relative humidity is high, ambient temperature is low, porosity is high, the accessible surface area of pores is important, the affinity of clay and water is high, the sample state results from de-wetting from a previous higher moisture state. Swelling clays are those that have the greatest affinity to water, due to their large surface area and high cation-exchange capacity.

In normal conditions of temperature and pressure, with a relative humidity below 70%, the water-content percentage in earth walls generally varies between 0.5 and 5%. It can be higher, especially in the presence of swelling clays and aggregates containing micropores and microroughness (Hall et al., 2009; Laurent, 1986; Hansen and Hansen, 2002; Heath et al., 2009; Maniatidis and Walker, 2008; Bourgès, 2003; Holl and Ziegert, 2002).

Eckermann et al. (2007) compared vapor-absorption measurements on various coatings. Although the measurements were not performed at the equilibrium-moisture content, they are helpful in making qualitative comparisons between the different samples tested. It appears that earth generally has a greater capacity to bind water vapor than concrete or gypsum. This water-retention capacity is linked to the porous and microporous structure of soil and to physico-chemical affinity between clay and water.

3.2 Shrinkage and swelling

During the drying phase, the soil undergoes a volumetric contraction or shrinkage, as a result of the withdrawal of water: clay platelets tighten due to the increase of capillary forces caused by the loss of water as suction increases. This shrinkage may in certain circumstances cause cracking, and so, it must be controlled. Conversely, when a dry soil is loaded with moisture, it expands as a result of the relaxation of capillary pressure and the swelling of clays having a high affinity for water.

The amplitude of shrinkage is limited if the water content used in the implementation of the material is low, the surface area and cation-exchange capacity of clays are small, the clay content is low, the porosity is high (the space between grains is not filled with a binding-clay phase), the soil contains vegetal fibers – the addition of straw is an effective way to prevent or limit shrinkage. The presence of salts in the soil can also alter the magnitude of shrinkage (Smith et al., 1985; Bourgès, 2003). The mechanisms involved are complex and dependent on the nature of the ions present.

The shrinkage of soil from its raw state to its implementation as a building material can vary between 1 to 20%. For rammed earth, the shrinkage percentage lies in the range of 1 to 3% (Robiquet, 1983; Gray anf Allbrook, 2002; Bourgès, 2003; Bouhicha et al., 2005; Smith et al., 1985; Heath et al., 2009; Walker and Stace, 1997; Bahar et al., 2004; Degirmenci, 2008; Hall et al., 2004; Kouakou and Morel, 2009; Maniatidis et al., 2007; P'kla et al., 2003; Vega et al., 2011).

3.3 Water-Vapor Permeability

The permeability to water vapor in a building material permits the definition of its moisture-exchange capacity between the inside and the outside of a building. The higher the permeability, the easier the exchange is between outdoor air and indoor air. It is, therefore, an important property to consider regarding comfort inside the house. For building materials, the factor of resistance to water vapor, μ, is used to characterize the permeability of a material to water vapor. It is equal to the ratio between the permeabilities of air and of the sample to water vapor. The higher the factor of resistance, the more difficult the moisture exchange between outdoor air and indoor air becomes.

For hygroscopic materials such as earth, which may fix a certain amount of air moisture, permeability increases with relative humidity. So the factor of resistance to water vapor, μ, decreases as the relative humidity increases. In theory, a single measurement of permeability is not sufficient to fully characterize the hygrometric behavior of earth.

For earth, μ varies between 5 and 13, and mainly depends on the pore-size distribution, the nature of clays and their content. Earth has a permeability to water vapor equivalent to that of cellular concrete, lightweight-aggregate concrete, gypsum and baked earth (Kleespies, 1994; CSTB, 2007; Utz, 2004; Bourgès, 2003; Hall et al., 2009; Volhard and Röhlen, 2009; NF EN 1745, 2002).

4. MECHANICAL PROPERTIES

4.1 Experimental precautions for the uniaxial-compressive test

The main mechanical property of earth that is of interest to builders is its uniaxial-compressive strength. To measure it, there are many available testing procedures, which do not, unfortunately, lead to the same results for the same types of materials. In most cases, experimental conditions influence the results and it is not the intrinsic compressive strength of the material that is being measured. Thus, these values cannot be used in a comparative manner.

The following precautions must be taken in order to properly measure the uniaxial-compressive strength of earth (Morel et al., 2007; P'kla, 2002; Walker, 2004; Olivier et al., 1997; Fontaine, 2004):

- Choose sample dimensions greater than five times the size of larger particles;
- Choose an aspect ratio between 1.5 and 2;
- obtain homogeneous samples;
- Let the samples stabilize in the desired hygro-thermal conditions;
- Coat the samples with a material as rigid as earth (a fine earthen mortar, for example) in order to obtain smooth and parallel surfaces;
- Use a ball joint above the top plate of the press if the surfaces are not perfectly parallel;
- Lubricate the contact between the sample and the press plates to reduce friction.

To measure the constitutive law and the elastic modulus of the specimens, care must be taken to measure the strain in the middle of the samples (using strain gauges for example) to avoid edge effects and the deformation caused by anti-friction systems (Mollion, 2009).

4.2 Elastic modulus

Young's modulus for earth is difficult to measure from a compression test. Its determination requires a sufficiently precise local strain measurement. It is, therefore, very difficult to find written sources with reliable values of the elastic modulus of earth. If surface roughness is imperfect, we can see a phase in which the curve increases progressively at the beginning of the testing, which corresponds to the crushing of surface ridges (Bui, 2008; Kouakou and Morel, 2009). This phase is not characteristic of the material and hides the elastic behavior of the original material.

To our knowledge, the only study that provides reliable measurements of the elastic modulus based on compression tests is that of Mollion who used measuring device adapted to strain measurement. Three strain gauges placed around the sample measure the deformation in the middle third of the specimen (Mollion, 2009). Other authors measure the elastic modulus using techniques based on the resonance frequencies of specimens (Fontaine, 2004) or the speed of ultrasound propagation (Bourgès, 2003). According to data from these studies, Young's modulus for raw earth is between 1 and 5.5 GPa. It gets higher depending on how low the porosity and moisture content are, and on how high the clay content and specific surface area are. However, the relationship between the composition of the earth, its microstructure and elastic modulus is not clearly established. The recommended modulus values vary but always lie below 1 GPa (Walker, 2001; Walker et al., 2005; NZS 4297, 1998; Maniatidis and Walker, 2003). This modulus lacks a clear definition: is the real Young's modulus of interest to builders, or do they just need an apparent modulus measured under certain conditions of stress?

4.3 Uniaxial-compressive strength

Standards often require testing protocols that do not measure the intrinsic strength of the material; the measure is partly influenced by the test devices. This is due in part to the fact that testing procedures for earthen materials are based on standard tests for cement concrete or fired-clay bricks whose mechanical properties are very different.

The most reliable results are listed. The compressive strength of earth viable for construction can vary between 0.4 and 5 MPa. For rammed-earth, the values are narrower from 0.5 to 3 MPa, the most common value being about 1.5 MPa (Azeredo, 2005; Barras, 2010; Bui, 2008; Bullen and Boyce, 1991; Fontaine, 2004; Hakimi et al., 1996; Jaquin et al., 2009; Kouakou and Morel, 2009; Maniatidis et al., 2007; Maniatidis and Walker, 2008; Mollion, 2009; Morel et al., 2003; Olivier, 1994; P'kla, 2002; P'kla et al., 2003).

The following parameters improve compressive strength: a high density, a low water content, a high clay and silt content, a high specific-surface area of the clays, good homogeneity, small grains. Based on the present state of knowledge, it is not possible to predict the compressive strength of a given soil without making experimental tests. Many parameters are involved in the mechanisms of cohesion of earth which determine its strength. The relationship between the microstructure of earth and its macroscopic-mechanical properties is very complex.

Property	Unit	Compacted earth	Molded earth	Fibred earth
Clay content	%	5 - 30	20 - 40	
Plasticity index PI	%	5 - 30	15 - 35	
Initial water content wini	%	5 - 15	15 - 35	
Dry density ρ	kg/m³	1600 - 2200 (1700 - 2200)	1200 - 2100 (1200 - 1700 for adobe)	300 - 1200 (600 - 800)
Ambient water content w	%	0 - 5%		
Drying shrinkage	%	1 - 3 (0.02 – 0.1 for CEBs, 0.1 - 0.2 for rammed earth)	1 - 20 (0.02 – 0.1 for adobe)	near 0
Water-vapor resistance factor μ		5 - 13		
Young Modulus E	GPa	1.0 - 5.5 (0.7 à 7.0 for cement stabilized earth)		< 1.0
Uniaxial-compressive strength Rc	MPa	0.4 - 3.0 (2.0)	0.4 - 5.0	
Tensile strength Rt	MPa	0.1 - 0.5 (0.5 - 1.0 for rammed earth and CEBs)		
Mass thermal capacity c	J/kg.K	600 - 1000 (~ 850)		
Volumetric-thermal capacity C	kJ/m³.K	960 - 2200	720 - 2100	180 - 1200
Thermal conductivity λ	W/m.K	0,5 - 1,7 (0,81 - 0,93)	0,3 - 1,5 (0,46 - 0,81)	0,1 - 0,3 (0,1 - 0,45)

Table 2. Mean values of earth thermal conductivity (credits: authors)

5. THERMAL PROPERTIES

5.1 Thermal Inertia

Inertia is the ability to store heat and release it slowly. It allows to shift variations in temperature inside the house from the outside, and to cushion temperature changes.

It depends primarily on the thermal mass of materials: the higher this capacity, the more the material may provide inertia to the building. Heat capacity, c, is expressed in J/kg.K. It is connected to the volumetric-heat capacity C in J/m³K by the relation C = c.ρ, where ρ is the mass density of earth. Earth's heat capacity, c, varies from 600 to 1000 J/kg.K with a mean value of 800 J/kg.K at 20°C (Laurent et al., 1984; Laurent, 1986; Goodhew et al., 2000; Goodhew and Allbrook, 2005; Hutcheon and Ball, 1949; Hill, 1993; Delgado and Guerrero, 2006; Wessling, 1974; Volhard, 2008; NF EN 1745, 2002).

For an earth-straw composite, x being the amount of straw, the heat capacity is:

$c = (1\text{-}x).c_{earth} + x.c_{straw}$

Similarly, the heat capacity of earth depends on its moisture content following a linear relationship, with θ being the volumetric-water content, and Cw = 4.186 J/m³ K:

$C(\theta) = C_{dry} + \theta.C_w$

In addition to the intrinsic-heat capacity of the material, the phase change of the water contained in the material contributes to thermal inertia: the evaporation of water causes cooling and the condensation causes warming. The energy exchanged is the latent heat of vaporization of water, which is of about 2400 kJ/kg (Kimura, 1988). This property specific to hygroscopic porous materials makes earth a natural phase-change material.

5.2 Thermal Conductivity

Thermal conductivity, λ, indicates the amount of heat (in W) that goes through an area of 1 sq meter/1-meter thickness when its interior and exterior faces differ in temperature by 1 Kelvin. It is expressed in W/m.K. The lower λ is, the more the material is insulating. Materials with λ < 0.065 W/m.K are considered insulating (Table 2).Earth is a porous unsaturated material. Heat transfer is related to several mechanisms: conduction in the solid, liquid and gas phases; convection; radiation; evaporation and condensation. To define conductivity in such a material is complex. Apparent conductivity is the value of conductivity reached by measure, which results from the combination of all the mechanisms mentioned above. The equivalent conductivity is the conductivity value of a homogeneous material equivalent to the considered material, which would have the same macroscopic-thermal behavior.

Conductivity increases with water content. For earth of about 1800 kg/m³ and suitable for rammed earth construction, it can vary from 1 to 1.2 W/m.K when the water content varies from 0 to 2%. For the same difference in moisture content, the change in conductivity can be more or less strong depending on the type of soil: not all earths have the same sensitivity to water. Earth by itself is not a good insulator, but when mixed with plant fibers and with a sufficient thickness, it can be used for the insulation of a building.

6. CONCLUSIONS

In conclusion from this overview, there is little reliable experimental data on the properties of raw earth for construction. This data is very fragmented as it often deals with one type of earth and focuses on only a few properties. The main properties of raw earth updated through this review are summarized in Table 3 for the three main types of earth implementation for construction: compacted earth, mold earth and earth with added fibres. The values given in the reference (Houben and Guillaud, 1989) are recalled in parentheses for comparison.

The thermal conductivity of dry earth depends primarily on its density and porosity. It varies between 1.5 W/m.K for dense earth (2200 kg/m³), and can drop to 0.10 W/m.K for mixtures of earth and hemp or earth and straw (500 kg/m³). Average values for several densities are shown in Table 2 (Boussaid et al., 2001, CSTB, 2007, Goodhew et al., 2000, Goodhew and Griffiths, 2005, Kleespies, 1994, Hutcheon, 1949, Laurent et al., 1984, Laurent, 1987, Maniatidis et al., 2007, Ola, 1987, Wibart, 2010).

ρ (kg/m³)	500	1000	1500	1800	2000	2200
λ (W/mK)	0.2	0.3	0.6	1	1.2	1.5

Table 3. Synthesis of the main properties of earthen materials for construction (credits: authors)

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SEISMIC RESISTANT ADOBE WALLS AND EARTHEN FRAMEWORK VAULTS AT THE COMPAÑIA DE PISCO CHURCH IN PERU

Pedro Hurtado Valdez

Theme 7: Ancient/Historic and Innovative Solutions for Damage Prevention and Performance Improvement
Keywords: Dome, earth, seismic

Abstract

On the occasion of the reconstruction of masonry vaults of the cathedral of Lima in the 17th century, master builders demanded the need for construction systems that would lessen the impact of earthquakes on the building. This situation resulted in an expert debate to determine the nature of damage resulting from earthquakes, the problems validated as being due to horizontal forces, and possible seismic-resistant solutions to be adopted, leading to the eventual introduction of earthen framework vaults. Contemporaneously, La Compañía de Pisco church was destroyed by the earthquake of 1687, which is why the most suitable type of structure was analyzed for erecting the new building, based on the conclusions from the debate on the cathedral of Lima. Finally, both temples had their vaults rebuilt with frameworks in 1691 and 1725 respectively, supporting them on properly reinforced adobe walls. Three hundred years later, the Pisco area was shaken by an earthquake that destroyed La Compañía de Pisco church, which had endured until then, revealing the notions of earthquake-resistance that the builders had used in the earthen construction of churches, but which was forgotten in the modern consolidation interventions of this temple.

1. INTRODUCTION

Since the dawn of the Spanish presence in Peru, stone and brick were materials regularly employed to build vaults and domes, constructed following the method of proportions and stability (Huerta, 2004). Promptly, Hispanic builders noted that the newly settled lands were consistently shaken by earthquakes of a high intensity, causing the collapse of most of the vaults, which until then were not prepared to deal with events of this magnitude (1).

During the 17th century, different ways to build masonry vaults had already been experimented with in many cities of the Viceroyalty of Peru; however, without having found a reasonable response in terms of time, economy and stability against earthquakes. Amid this building landscape, earthen-framework vaults were introduced in the mid-17th century.

2. THE CATHEDRAL OF LIMA AND THE TECHNICAL DEBATE OF MASTER BUILDERS

A crucial moment for the development of framework vaults in the Viceroyalty of Peru was the case of the reconstruction of the vaults and the walls of the cathedral of Lima. The original masonry groin vaults, following the earthquake of 1609, were badly damaged, so an arduous debate between the main builders of the city occurred to determine the best way to repair or even to replace these vaults. The dialogue was focused on how to stabilize the thrust of the vaults towards the walls during an earthquake, by increasing their thickness. The subsequent findings of the damage that earthquakes caused in these types of vaults motivated an anachronistic use of ribbed vaults. The vaults of the cathedral of Lima were rebuilt with this system, with the conviction that the concentrated thrust in a ribbed vault would guarantee their stability during earthquakes. Therefore, it would be sufficient to provide the adobe walls with abutments, located at thrust points, with a thickness sufficiently able to absorb out-of-plane forces (2).

A new turning point was marked by the 1687 earthquake, which caused the collapse of the new vaults, leading again to the reflection on the best way to rebuild the vaults of the cathedral. Then, Fray Diego Maroto offered the Ecclesiastical Council a vision of structural safety from the framework vaults built by himself some years before in the Church of Veracruz and the Church del Sagrario, proposing to reconstruct the vaults of the cathedral using this same system (3). Pedro Fernandez Valdes wrote that adobe abutments could not