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RAW EARTH CONSTRUCTION: FIRST ANALYSIS OF ITS FROST RESISTANCE

Lassana Traoré[1,2], Claudiane Ouellet-Plamondon[2], Fionn McGregor[1], Antonin Fabbri[1],

[1] LGCB-LTDS, UMR 5513 CNRS, ENTPE, Université de Lyon, France
[2] ETS, Université de Montréal, Canada

Abstract: Raw earth constructions, under a variety of forms, have been part of human civilization since thousands of years. As an ancient building material, it raises today a huge interest by architects and engineers considering its low ecological impact and its thermo-hygro-mechanical performances. Raw earth is a heterogenous material and is considered as multi-phase (solid matrix, water and air), therefore such material presents multi-physical properties. The highly thermo-hygro-hydro-mechanical coupled nature raises a complexity of laboratory protocols to assess its standard performances. Water in the material, under liquid or vapor phases, plays a key role in its performances as a building material. What's more, in cold regions, the cyclic effects of water freezing and ice thawing on earthen houses cause an extreme moistening which represent a major risk of frost damage. In that context, this paper aims at presenting a review of the principal knowledge on the frost durability of earthen constructions.

1. INTRODUCTION

Long suffering from a lack of acceptability, earthen constructions are regaining now more and more interest considering sustainable development and ecological purposes. Several earthen construction technics exists. They can be gathered as the "wet" techniques (plastic state of the soil) and the "dry" techniques (close to Optimum Proctor state).

All the load-bearing earthen walls have in common an average thickness of at least 50cm and a basement with a height that can reach one meter in order to limit capillary rises. For the "wet techniques", mainly cob (fi 1c) and adobe (fig 1.d), the addition of vegetable fibers (like straw) is essential to limit the shrinkage during desiccation. The adobe is a manually shaped brick and is left to dry in the open air several days before they are used in masonry. Cob consists in the construction of layers of monolithic walls stacked without the use of formwork. The most common "dry techniques" are rammed earth (fig1.e) and compressed earth blocks (fig1.f). Like cob, rammed earth leads to monolithic walls. But it requires to successively compact thin layers of soil moistened at its optimum water content and placed in a formwork. The CEB technique appeared in the nineteenth century. This technique consists of making bricks of compacted soil by using a press (manual or dynamic) and to assembly them with thin joint of earth, lime or cement-based mortar.

The most common non-bearing technique using earth is wattle and daub (cf. fig. 1a). It is a "wet technique" which consists in filling a wooden load-bearing lattice with an earth and straw mixture. Finally, crude earth can be used for rendering purposes (cf. fig 1b). If they are mixed with bio-based materials, earth plasters can also be used to improve thermal insulation.

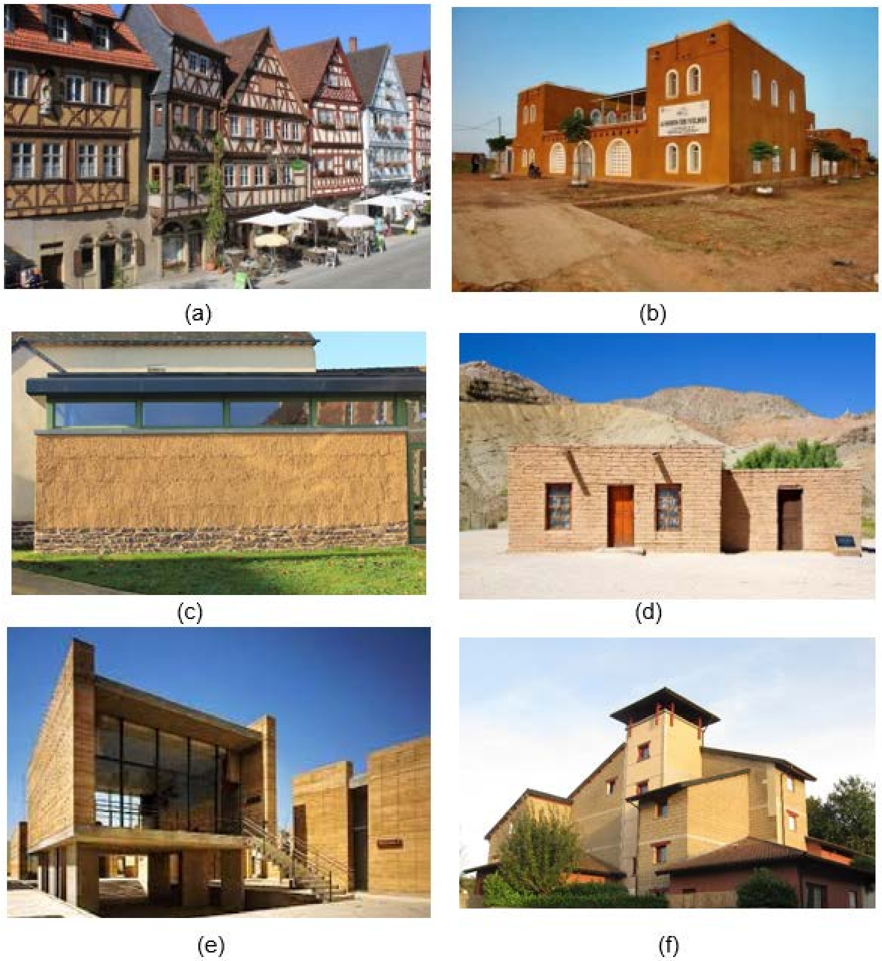


Figure 1: (a) Timbered houses in Ochsenfurt (Allemagne)-(b) “Maison des Yvelines” rendering with raw earth in Ouroussogui (Sénégal)-(c) Cob wall of the library of Muël (France)-(d) “El casa de Adobe : el poder en el desierto” in Chihuahua (Mexico)-(e) Oaxaca art school in Mexico-(f) “Le Domaine de la Terre” in Villefontaine (France)

Compare to modern constructions, earthen constructions have a low embodied energy because raw earth is a local material which can be extracted directly on ar around the construction site and allow to cut down). energy for transformation (fig2.a) and greenhouse gas emissions (fig 2.b).

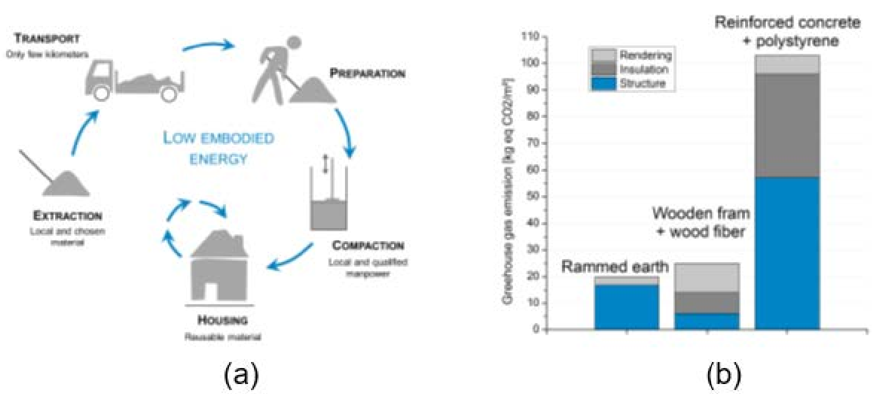


Figure2: (a) embodied energy during earth construction – (b) comparison of greenhouse gas emissions (Soudani 2016)

Also, raw earth is a reusable material with a limitless lifespan. By re-wetting, the material can be reused easily (Bui 2008). Nonetheless, new practices raise the question of their low carbon footprint. For instance, industrial prefabricating of the rammed earth in the aim to reduce the time of construction, stabilization of raw earth by adding between 5% to 10% hydraulic binder as lime or Portland Cement to the soil in order to improve its strength, its durability and its water-resistance (Van Damme and Houben 2018). Furthermore, casting earth can be obtained by mixing adjuvants as superplasticizers with raw earth for self-compaction in the framework (Ouellet-Plamondon and Habert 2016).

In addition to its ecological impact, earth in construction can be used to improve the in-door air quality. Indeed, this material is hygroscopic which is characterized by its ability to capture and release water molecules contained in the surrounding air. In this way, compared to conventional materials, raw earth possesses excellent ability to regulate moisture humidity of indoor environment (fig5.a) associated with an interesting capacity of heating inertia for heat storage (fig4), hence a high capacity to stimulate hygrothermal wellbeing for inhabitants (Woloszyn, et al. 2009). These hygrothermal properties may also cut down energy consumption caused by air conditioning or ventilation systems and limit mould growth (McGregor, et al. 2014).

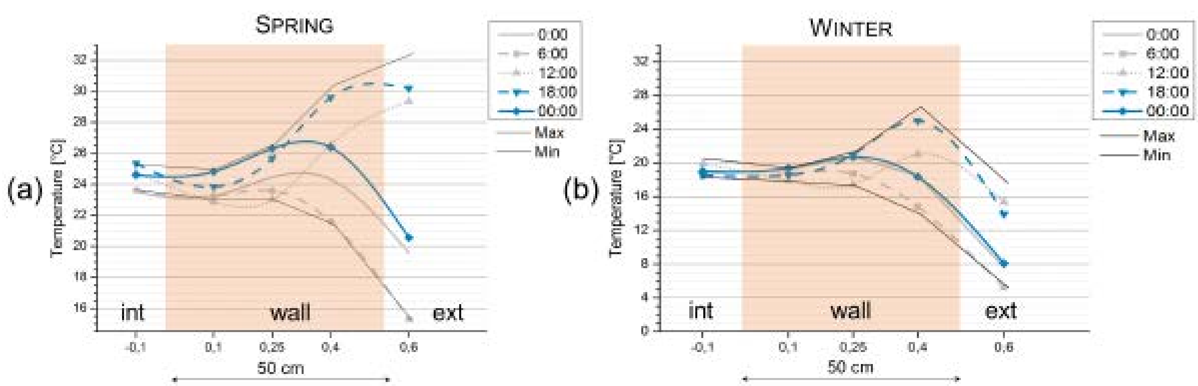


Figure 3 : Thermal comfort zone provides by raw earth heating inertia (Soudani 2016)

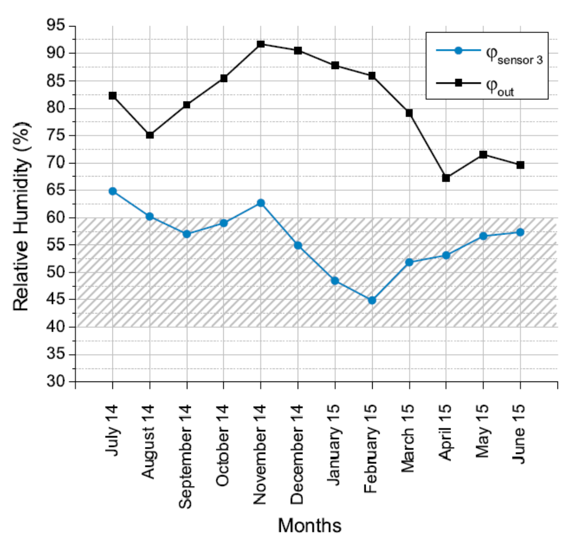


Figure 4: Self-regulation of moisture humidity in indoor environment (Soudani 2016)

The low ecological impact of raw earth associated to its high performances to regulate indoor temperature and moisture are inviting to reuse this ancient building material for modern construction. Also, earth construction represents a rich heritage. Indeed, one third of the world population lives in earthen houses. But their maintenance and their rehabilitation rest on an artisanal know-how that curb establishment of scientific consensus. This lack of scientific knowledge is also explained by the heterogeneity of soil and the complexity of the behavior of raw earth as an unsaturated soil. In this case, the water content is the governing parameter of the thermo-hydro-hygro-mechanical (THHM) behavior of the earth structure. In addition, in cold regions, the presence of liquid water raises the question of the freeze/thaw resistance of earth constructions. Better understandings of the multi-physical behavior of raw earth is necessary to evaluate its performances and its durability related to its sensitivity to moisture.

This paper investigates the durability of earth construction as a sustainable building material subjected to frost/thaw cycles. For that purpose, it mainly focuses on previous studies on this subject. At the end, it presents some trials to further exanimate the frost damage on earthen construction. The following in this paper deals with the impact of moisture content to its THHM behavior, the in-pores crystallization process, poromechanics and coupling models for heat and mass transfers. Analysis mainly focuses on the liquid saturation degree as the key parameter which influences the resistance of raw earth to frost/thaw cycles and therefore on its durability in cold countries.

2. CHARACTERIZATION OF EARTHEN MATERIALS

2.1. Raw earth characterization

Raw earth is a soil composed of aggregates (sand, gravel) bounded by a continuous clay matrix which can be considered as the binder. In fact, it provides cohesion and resistance to the material.The main physical properties which are commonly used to classify a soil are its granulometry (the particle size distribution), its cohesion (ability to reduce to resist to tensile stress) and its plasticity (potential to deform without cracking) (Van Damme and Houben 2018). However, in their approaches to study raw earth in the laboratory, many authors (Bui 2008) , (Chabriac 2014) , (Champiré 2017) have shown the limits of the use of these criteria to identify a good “raw earth” for construction purpose.

Actually, the proportion of clay must be enough to ensure good resistance and strength of the material, but the proportion of expansive clay must remain limited (less than 50% of the total amount of clay) in order to avoid important shrinkage / swelling. However, these thresholds are only indicatives, and the granulometric approach is quickly limited because of the important differences in nature of the granulometric clay fraction (<2 µm), which considerably impacts microstructure and the affinity to water. In fact, a large presence of the montmorillonite clay mineral may lead to important dimensional variation due to swelling which can induce cracks or even the loss of building stability. Other types of clay minerals such as chlorite, illite, or kaolinite are less sensitive to swelling-shrinkage phenomenon then they are more suitable for earthen constructions (Van Damme and Houben 2018). In consequence, there are no fixed rules about the proportion of clay, silt, sand and gravel that a "good earth" must contain (Champiré 2017), and many authors found different limits for particle size distribution (table 1).

Table 1: Limits of particles size distribution proposed by various studies (Champiré 2017)

Author/Name	Clay	Silt	Sand and Gravel
IETcc ,1971	10-40%	20-40%	10%-20%
McHenry, 1984	15%	32%	53%
Keable, 1996	5-15%	15-30%	50-70%
Keefe ,2005	7-15%	10-18%	45%+30%
Peter Walker et al, 2005	5-20%	50-80%	10-20%

Given that, earthen construction focus on reaching another parameter: the optimum density that can be obtained. Indeed, several studies indicate that higher is the dry density, higher is the mechanical strength of earthen materials. For the “dry techniques”, along similar lines to those of the Proctor test, the optimum density is reached for an optimal water content of fabrication which allows an optimal arrangement of the grains during compaction. For the “wet techniques” the optimum density is also reached through an optimal manufacture water content, but the densification process is different, since it is mainly induced by drying shrinkage.

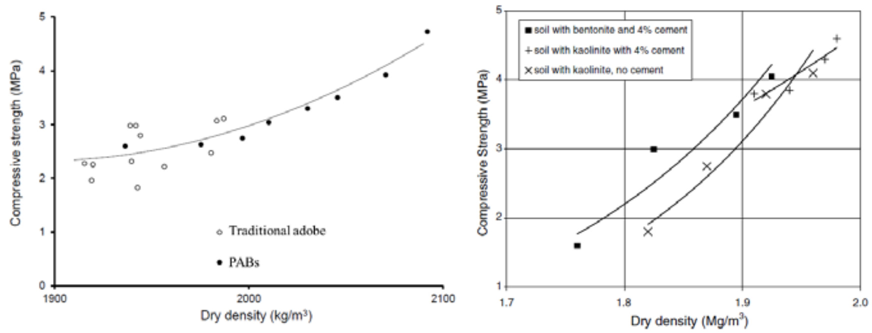


Figure 5: Evolution of compressive strength as a function of dry density (Champiré 2017)

However, if relationships between dry density and compressive strength can be drawn for a given earth, it is not possible to generalize it. Indeed, Table 2 highlights a large variability in the mechanical characteristics of the rammed earth, not attributable solely to the density variation of the materials tested.

It follows that only establishing the intrinsic parameters of a soil is not enough to conclude on its mechanical performances and its durability for construction. Regardless, building an earthen house at the optimum water content allows to reach a better mechanical resistance.

Table 2: Non-constant evolution of compressive strength with dry density (Champiré 2017)

Dry density ρ_d (kg/m³)	Strength R_C (Mpa)	Size (cm)	Slenderness
1850	3,88	Cyl d10 h20	2
1850	2.46	Cyl d10 h20	2
1763	0.62	30x30x60	2
1971	0.84	31x30x60	2
2027	0.97	32x30x60	2

2.2. Impact of water content on the performance of earthen samples

In addition, the difficulty to *a priori* identify a good soil for construction is coupled with the difficulty to assess correctly the performance of earthen samples. The main reason of this difficulty is the impact of the amount of water which remains within the porous network of the sample on its performance.

One sound example is the mechanical performance: compressive strength and stiffness can be divided by 4 and 3, respectively, when the water content increases by 2 to 3 percentage points. For better mechanical performances, the water content should be maintained as low as possible (Table 3). An excess of moistening jeopardizes the stability of the earthen structure. Investigating in the laboratory the hydromechanical behavior of raw earth raises some complex questions about the choice of the basic representative volume (Bui, Morel and Hans, et al. 2009) or the representative test protocol (uniaxial compression test or triaxial test) (Chabriac 2014), (Champiré 2017). Indeed, some parameters as the geometry of a sample or the confinement during the test have an important impact on its real load (Miccoli and Fontana 2014). A direct measurement of the compressive strength can give aberrant results (Aubert, et al. 2013) or can be modified considering the anisotropy in rammed earth (Bui and Morel 2009).

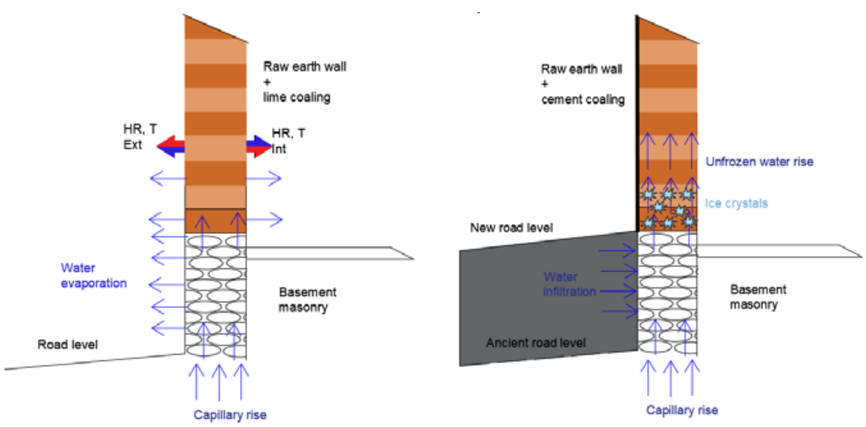
Table 3: Evolution of mechanical properties (E_{tan}, q_{max}) with water content w (Champiré 2017)

w (%)	E_{tan} (MPa)	q_{max} (MPa)
11	819	0,38
10	972	0,59
9	1098	0,79
8	1458	1,23
7	1627	1,28
6	1971	1,7
5	2039	1,78
4	2065	1,93
3	2081	1,95

3. ANALYSIS OF THE FROST RESISTANCE OF EARTHEN MATERIALS

3.1. The issue of durability due to the impact of frost/thaw cycles

The previous section underlined that raw earth is very sensitive to moisture. A basement masonry with stones and pebbles is the fundamental element for preventing any contact between moisture and earthen wall. As a perspiring material, the presence of cement coating blocks the evaporation of the water vapor and capillary lifts (Scarato and Jeannet 2015) . This condensation is therefore harmful for the durability of raw earth structures even more if it is associated to frost/thaw.



(a) (b)

Figure 6: Illustration of moisture ingress in a rammed earth wall with sufficiently exposed basement masonry (a) and in a wall with inadequate basement masonry (b)

In this way, liquid water and ice are defined as the two main actions jeopardizing the durability of earth buildings (Fabbri, Morel and Gallipoli 2018). Indeed, in cold regions, architects and artisans frequently observe pathologies related to the cyclic effect of water freezing which may lead to surface disorders or to a complete collapse disaster of the building (Scarato and Jeannet 2015). This high level of liquid saturation degree reduces the resistance and the consistence of the wall and accelerates its collapse during thaw periods. There are two types of frost damages: surface damage and internal damage. The former is when the deterioration is visible with the development of cracks (peeling) then weight losses. The latter occurs in the microstructure: frost/thaw cycles can generate a loss of intergranular bonding therefore a fall of its resistance and its stability (Fabbri, Morel and Gallipoli 2018). It is the most prejudicial for the stability of earth construction.

In fact, the phenomenon of capillary rise generates a water infiltration in the porous media of the raw earth. As soon as the wall is exposed to low temperatures, the water in the pores can freeze. The change of phase from liquid to ice creates a 9% volume expansion. When this extra volume can no longer be contained within the pores volume, it is expelled under hydraulic overpressure (Powers and Helmuth 1953). Therefore, if the tensile strength of the solid matrix become lower than the stress induced by the increase in hydraulic pressure, then microcracks develop and damage the intergranular bonding of the material. This is more likely due to the theory of overpressure according to which unfrozen water is transferred from frozen pores to an outlet. Moreover, the water content in the material would increase because of the phenomenon of cryo-suction (water absorption by ice crystals) (Vignes-Adler 1976). This is a consequence of the thermodynamic balancing mechanism of pressure gradient between the distant liquid and the unfrozen water close to the ice front which is in depression.

3.2 Some approaches to model frost damage on raw earth

Owing to its water affinity, raw earth is a multi-physical material (Lei, et al. 2014). In fact, rammed earth or CEB is being carrying loads then mechanical stresses appear. In addition, when it is exposed to environmental conditions (pouring rain, wind, snow, capillary rise), its hygrothermal gradients may change and impact its hydromechanical behavior. Moreover, if phase change phenomena as water freezing and ice thawing occurs within the porous network, its thermo-hygro-hydro-mechanical behavior becomes strongly coupled and complex to analyze (Yin, et al. 2018).

The phenomenology of freeze-thaw impacts on raw earth materials is complex because of the unsaturated state of the raw earth: solid matrix, liquid water, ice crystals and water vapor, the chemical reaction with cement in the case of stabilized raw earth, the hysteresis associated to soil-water relationship and the ice lens formation during freezing process (Yin, et al. 2018). In this case, many assumptions are necessary to evaluate the impact of water content on the durability of earth construction under frost-thaw cycles.

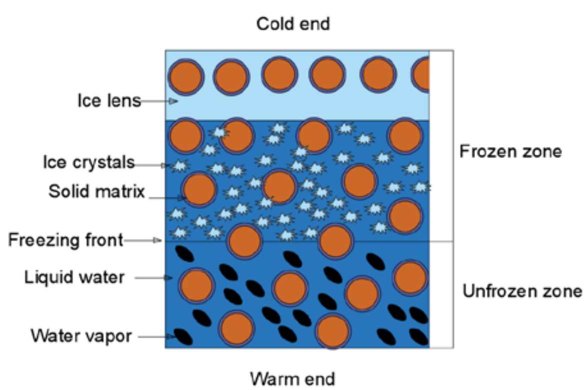


Figure 7: Microstructural complexity of frost/thaw impact on unsaturated material as raw earth (Yin, et al. 2018)

The frost damage of raw earth is mainly due to the process of crystallization of liquid water in the porous media. An extension of the concepts of saturated poroelasticity to unsaturated poroelasticity provides the state equations of unsaturated poroelasticity (Coussy and Monteiro 2007). In pores crystallization involves two distinct physical processes which occurs simultaneously. On the one hand, there is an expansive liquid to ice phase change (liquid water is about 9% denser than ice). If the matrix is not deformable, the excess of unfrozen liquid water in the freezing zone is drained under hydraulic pressures to the eventual air voids. This step also includes the micro-cryo-suction process within the pore entry distribution during which liquid water is drained by the ice-crystal to balance their chemical potentials. This drainage impacts the liquid-ice interface. On the other hand, a mechanical deformation of the porous media occurs due to the volume expansion during the phase change due to the difference of density between the liquid water and the ice crystal. This step explains the mechanical actions of partial pressures on the interfaces with the solid skeleton (Coussy 2005).

A better understanding of the poromechanics of freezing materials as raw earth need to pay attention to some microscopic properties as liquid saturation and pore radius distributions (Coussy 2005).

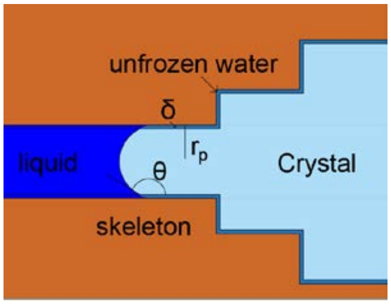


Figure 8: Partial freezing evolution within porous media by decreasing pore radius

Using Gibbs-Thomson equation, some fundamental basis for in-pore crystallization can be underlined. Indeed, during freezing process, when the temperature is below the freezing point, ice crystals are formed in biggest pores at first and the ice crystals start to grow into smaller pores with the decrease of temperature. The liquid saturation degree S_L which represents the volume fraction of water remaining unfrozen at the temperature T is called the Soil Freezing Characteristic Curve (SFCC). In addition, considering the equilibrium at the liquid-ice interface (which is assumed to be spherical), it is possible to link the temperature of the phase change to the radius of the pore in which the phase change occurs (Brin et al., 1977):

[1] $r_p \approx \frac{2\,\gamma_{cl}}{\Sigma_m\,\Delta T} + \delta$

Where γ_{cl} is the energy of the liquid/ice interface, Σ_m the entropy of melting per unit of crystal volume, $\Delta T = T_0 - T$ represents the undercooling temperature and δ the layer of unfrozen water.

The use of this expression can allow to draw the pore size distribution using the SFCC, or alternatively may allow to indirectly determine the SFCC using MIP or water sorption/desorption measurements (Fabbri and Chong 2013).

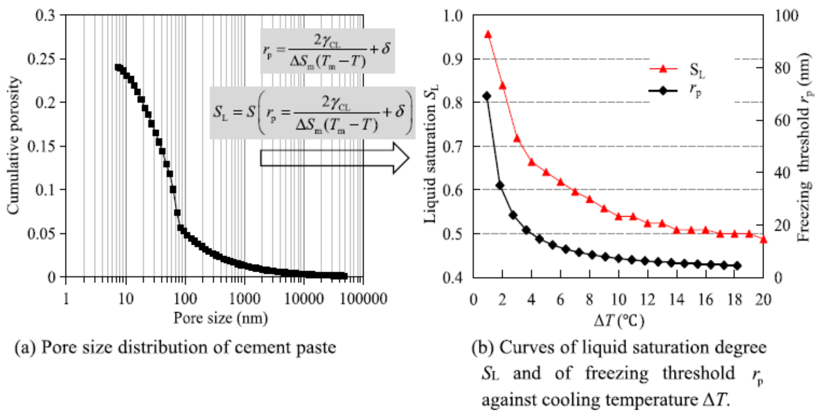


Figure 9: Calculation of the liquid degree saturation from pore size distribution during freezing (Liu, Qin and Wang 2018)

3.3 The heat and mass transfer

When an unsaturated material is exposed to frost/thaw cycles, the freezing/thawing process also includes an important source from conductive heat flow and mass transfer in the porous media; that is more difficult to model mathematically. In an unsaturated soil, some hydrothermal parameters as thermal conductivity λ, hydraulic conductivity are functions of the temperature, soil suction potential, and water content. Direct measurements allow to estimate the thermal properties for raw earth but for its hydraulic properties, their experimental measurement can be difficult. But it is well-known that the hydraulic conductivity is reduced by pore ice in a partially frozen soil (Azmatch, et al. 2012), (Newman and Wilson 1997).

Also, there are many theoretical models that focus on coupling heat and mass transfer equations such as Philip and de Vries model (1957), Künzel model (1995) or Wilson and Newman model (1996). However, experimental tests are needed to choose and confirm the best heat and mass transfer model for raw earth construction. In their approach for modeling heat and mass transfer in freezing unsaturated soil, (Newman and Wilson 1997) showed that their model can predict the ice content and the temperature of an unsaturated soil (Figure 10).

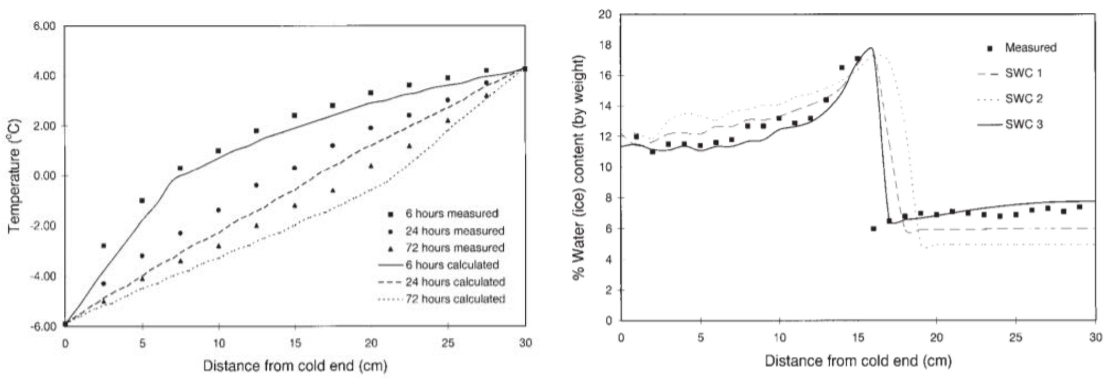


Figure 10: Ice content and the temperature from freezing source distance (Newman and Wilson 1997).

4. CONCLUSION

With a low embodied energy and greenhouse gas emissions, the use of raw earth for construction is motivated by ecological ambitions. It provides good hygro-thermo-mechanical performances for the inhabitants' comfort and the durability of the structure. The raw material is abundant and reusable. The durability of earthen houses is governed by the water content in the material, which is the key parameter impacting the THHM properties. When good technical practices are not respected, an uncontrolled moistening of raw earth can jeopardize its mechanical stability and so its durability. The damage caused by water can be induced by frost-thaw cycles, for example. In this case, the microstructural deformation modifies the macroscopic behavior during the heat and mass transfer. This multi-physical behavior is quite difficult to model because of the complexity of raw earth. It seems interesting to better investigate the impact of frost damage with a thermo-poromechanical approach of crystallization in pores and a coupling model of heat and mass transfers during freezing to assess the frost resistance of earth constructions in cold regions and eventually lead to an optimized durability for newly built or restored buildings.

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