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Hygrothermal characterization of rammed earth according to humidity variations

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Abstract. Rammed earth construction is built by compacting humid soil into formworks layer by layer, using clay fraction as only binder between the grains, without firing procedure. At this stage, the material is unsaturated, and capillary forces thus act to add cohesion between particles. Indeed, a peculiarity of this material is its high hygroscopic capacity, which allows water vapor to be absorbed and desorbed into the clay matrix. The variation of hydric state in the material leads to a variety of mechanical and thermal properties. Consequently, the complexity in studying this material is due to the strong dependence of many parameters on the moisture content and still few data are available in the literature on this subject for rammed earth materials. A soil used for an existing rammed earth building in Lyon is here characterized in order to determine its hygrothermal properties. Earth conductivity was firstly characterized in a reference dry state, then the influence of humidity variations was investigated. Sorption and desorption isotherms were determined to investigate the ability of the material to store and release humidity. Thermal conductivities were measured at different relative humidity, to put into evidence the influence of environmental conditions.

1 Introduction and background

The report prepared in 2018 by the International Energy Agency (IEA) for the Global Alliance for Buildings and Construction claims that the buildings and construction sector has a key role in the fight against climate change: it is responsible for 36% of final energy use and 39% of energy- and process-related emissions in 2017 [1]. A significant part of the energy consumption and emissions are due to the operative life of the building and are related to its energy performance. Other emissions are generated during the construction phase, due to the transportation, the construction process and the use of polluting construction materials. Consequently, finding construction materials with a low carbon footprint is essential.

In this context, the use of raw earth materials has several advantages. It is a local resource that does not require long-distance transport and energy-intensive processes, as is the case for fired bricks and cement. Moreover, it allows the reuse of excavated earth during construction, contributing to the development of a circular economy. Thanks to its recyclability at the end of life, the use of raw earth limits the generation of construction and demolition waste. Finally, the thermal inertia and hygroscopic properties, i.e. its capacity to retain or release moisture, can contribute to the passive regulation of the indoor environment and reduce the need for energy consumption in earthen houses. Therefore, it is a particularly interesting material with regard to the climate challenge of reducing building-related emissions and energy use.

The present study focuses on the use of rammed earth (RE), a technique of construction for raw earthen buildings where the soil is compacted, in a humid state, into formwork layer by layer. A moisture content of around 7-12% is generally used to prepare the soil before the compaction. The compacted wall is finally able to stand with as only binder the clay fraction in the soil.

The complexity of working with RE is due to the variability of its properties. The spatial variability of soil makes this material non-standardized. Mechanical and hygrothermal properties of RE are affected by the grain size distribution, the kind of clay fraction and the porosity network of the soil matrix. Compared to the usual building materials like concrete, the phenomenon of moisture transfer through the walls is not negligible. When the quantity of water within the earth fluctuates significantly it impacts both the mechanical and hygrothermal properties, adding others factors of variability. Several studies have already investigated the mechanical properties of RE and its sensitivity to water, less extended is the research on the thermal properties of this material according to humidity variations [2,3]. In particular, thermal conductivity is a fundamental datum to describe the hygrothermal behavior of construction material, and its heat transfer properties and predict the heating demand of RE buildings. In the case of strong hygrothermal coupling, such as for RE material, thermal conductivity can vary with the adsorption and release of moisture. Soudani [4] found the thermal conductivity of RE increased by 30% between a dried state and a water content of 2%. Consequently, it is important to define the measurement

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conditions (both temperature and humidity) precisely when measuring thermal conductivity.

The sorption curve represents the evolution of the water content of a porous material according to the relative humidity of its environment at equilibrium state at a constant temperature. The adsorption curve follows the increase in water content w with increasing relative humidity *(RH),* while the desorption curve follows the decrease in w with decreasing *RH*. Generally, the function of the moisture content of a desorption process presents higher values than the one belonging to the adsorption process [5]. Consequently, the equilibrium moisture content at a defined level of *RH* can differ [6]. This hysteretic behavior is due to a combination of different effects, i.e. adsorption metastability and/or network effects (ink bottle effect) [7]. For a construction material that undergoes daily and seasonal *RH* oscillations, hysteresis may lead to the storage of moisture. To further investigate this phenomenon, intermediate sorption loops can be determined to estimate how the material behaves under different cycling conditions of *RH.*

The work here presented aims to study the hygrothermal behavior of RE, to investigate the impact of hygrometry on the thermal properties of the material.

2 Materials and Methods

2.1 Samples preparation

The earth used is the same of the multi-story office building in Pisé in the district of Confluence, Lyon. Compared to the soil of the building, the one used for the experiment was sieved to 5 mm to allow the production of samples to be tested at a laboratory scale [8]. A complete description of the soil is reported by Chitimbo et al. [9]. The soil was excavated from a region in South-eastern France, in St Quentin Fallavier in the Auvergne-Rhone-Alpes [10]. The soil sieved at 5 mm presents about 15% of clay, 15% of silt, 54% of sand and 16% of gravel. The grain size distribution is reported in **Fig. 1**. The Atterberg limits determined by Casagrande and Penetrometer method are in good agreement. The liquid limit is equal to 30%, the plastic limit to 19.1% and the plastic index is estimated about 10.9%.

The samples prepared have a diameter of 7 cm and a thickness of 2 and were compressed using a hydraulic press, reaching a maximal compression stress of 7,7 MPa. The average density of the 8 samples prepared is 2022 ± 4 kg/m^3. This density is slighlty higher than the one of the building blocks, at 1900 kg/m^3.

All the samples were initially dried at 105°C for 24 h until reaching constant weight. This procedure allowed us to determine the dry mass m_0. The water content of the samples w is expressed as a proportion, defined as follows:

$$w = \frac{m_w}{m_0} \tag{1}$$

where m_w is the mass of water in the sample and m_0 the dry mass.

The evolution of the mass was monitored by weighing the samples at 24-hour intervals. A balance with a precision of ±1 mg was used for the test . The equilibrium criterion was defined as a condition on the variation in the mass of the sample according to the following formula by Rode [11]:

$$\left(\frac{m^{n+1} + m^n}{m^n} \times 100\right) < 0.015 \tag{2}$$

where m is the mass daily measured and the relative percentage of mass variation is less than 0.015% for 2 consecutive days. The criteria defined by Rode is adapted for light insulating materials and suggest a variation smaller than 0.1%. This value was modified to 0.015% to maintain satisfactory precision at the equilibrium state in our study.

The samples were placed in sealed boxes at room temperature, controlled by a climatic system to be around 22±2 °C. The relative humidity was imposed by a saturated salt solution at the bottom of the box or by silica gel in case of a dry environment. Different salts were used to prepare the saturated solution (i.e. KOH, CH_3CO_2K, $MgCl_2$, NaBr, NaC, KCl and K_2SO_4) at different relative humidity (9%, 22%, 33%, 58%, 75%, 84% and 97%) [12,13]. A sensor in each box allows the monitoring of the evolution of both temperature and relative humidity. Hygrothermal sensors with an accuracy of ± 2% RH and ± 0.5 °C were used. To avoid grain loss, the samples are wrapped before packaging in a thin fabric that let the humidity cross without absorbing moisture.

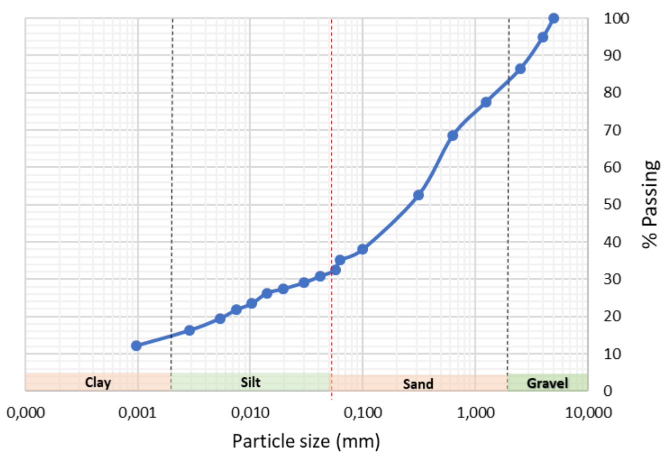

Fig. 1. Particle size distribution for soil sieved at 5mm.

2.2 Sorption/desorption and intermediate isotherm loop

For measuring sorption and desorption isotherm, the samples need to reach equilibrium at progressive steps of relative humidity, as described by the international standard ISO 12571:2013(E) [14]. After the drying procedure in the oven, 4 samples were moved in the order at 33%-58%-75%-84%-98%-84%-58%-33%-9% RH. Other four samples were used to measure an intermediate isotherm loop from 85% returning at 33% and 9%, to verify the presence of hysteresis when subjecting the samples to intermediate RH levels, as generally happens in building operative conditions.

2.3 Thermal conductivity

The conductivity of the samples was measured at the corresponding RH imposed (same as the sorption isotherm). The use of Hot-Disk apparatus allowed to perform quick dynamic measures, maintaining the samples in the conditions of the reached equilibrium. At the same time, this device does not require the use of big samples, allowing a reduced time for the conditioning.

The Hot Disk (Transient Plane Source method) is composed of a thermal sensor (radius = 6.403 mm), consisting of a nickel double spiral, with Kapton insulation. The thermal sensor is connected to a thermal analyzer that can show the results of the measurement in real-time. A constant electrical power in the sensor diffuses heat in the material and the detection of the temperature variation in the samples allows to determine the conductivity and diffusivity.

The sensor is placed between two samples of identical size and geometry in order to obtain a symmetrical configuration (**Fig. 2**.). To improve the quality of contact, a 500g weight is placed on the samples. Finally, a cover is placed on the samples to avoid any influence of air movement or temperature variations in the room. The measurement was made in the shortest time possible (1-2 min), because once the sample is taken out of its box, it is no longer in equilibrium with the surrounding environment. It was verified that for the short time of the measuremnts the variations in the water content in the samples are lower than 0.015% as expressed in formula (2), assuring the samples matain the equilibrium moisture content during the test.

The setting for the measure was defined to satisfy the requirement to validate the results given by the producer: (i) total characteristic time maintained within a range of 0.33–1.0 s, (ii) standard deviation in the temperature lower than 10^{-4} K, (iii) temperature increment of the sample between 2 and 5 K. The setting for the thermal sensor was then defined as a power equal to 110-120 mW and time of measure equal to 20 s. The error of measurement was taken as the maximum between the standard deviation measured by the device and the 5% of the detected value, indicated as the accuracy of the Hot-Disk apparatus.

3 Results and discussion

3.1 Sorption/desorption and intermediate isotherm loop

The sorption curves are presented in Fig. 3 as an average of measurements on 4 samples. The standard deviation, in the range of 0.01% to 0.1% water content, is almost not visible on the graph. The curve resents a similar behavior with the type II sorption isotherm described by IUPAC, generally presented by clayish

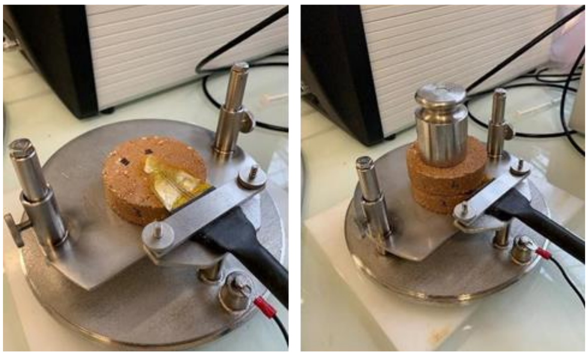

Fig. 2. Preparation steps for the Hot Disk measurement.

materials [6]. The maximal adsorption reaches values of 3.8% of water content, in the range of common literature values [15,16]. The adsorption curve has an almost constant slope between 9% and 75% relative humidity. The slope drastically increases for values of relative humidity higher than 75%. Analyzing the desorption branch, the hysteresis reaches the highest value at 84% RH, at this point the difference in moisture content between the sorption and desorption branches is about 0.60%. The hysteresis is reduced to 0.30% for the intermediate levels of relative humidity at 58% and 33% RH.

The intermediate loop shows the desorption from 84% to 33% and 9% RH. The increment of hysteresis is lower than 0.26% of moisture content when the material undergoes relative humidity lower than 84%, less than half compared to the desorption branch. This result indicates the risk of an excessive storage of moisture in RE walls if they reach elevated moisture content.

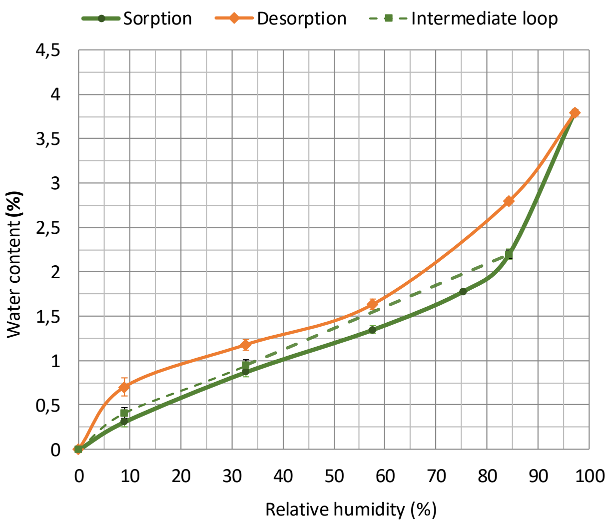

Fig. 3. Sorption – desorption isotherm and intermediate loop.

3.2 Thermal conductivity

Ce results of the thermal conductivity are reported as an average value of 8 measurements on two pairs of samples with the hot-disk apparatus. The dry thermal conductivity λ_{dry} presents a value of 1.34 W/mk, slightly higher compared to the literature value on RE materials, but justified by the high content of sand and the elevated density of the samples [17]. Considering Fig. 4. the disposition of the values seems to reproduce the shape of the sorption curve, indicating a clear relationship between the conditions of measure (relative humidity) and the increment of thermal conductivity. The thermal conductivity increases by about +19% around from 0 to 75% *RH*, while the highest increase occurs at 97% RH% up to +39% compared to λ_{dry}.

Fig. 5. shows the thermal conductivity versus moisture content. It confirms that the increment of moisture is almost linear with respect to thermal conductivity, with an R^2 equal to 0.99. The standard deviation between the repetition of the measurement on the same sample is always under 3%, even considering a different point of measurement on the same sample. This result assures good repeatability of the measure.

As showed by Chabriac [15] on a larger batch of soils, the knowledge of the density is not enough to predict the dry thermal conductivity of RE. Nevertheless, it is possible to identify a global tendency that relates higher densities to higher $\lambda_{dry.}$ The difficulty in the prediction of this parameter is probably due to the complex porous networks linked to the grain size distributions, the type of clay minerals in the soils and the compaction process. On the other hand, for the same earth compacted at different densities, it may be possible to identify a linear relationship between its density and thermal conductivity, as illustrated by different studies [15,16]. In addition, the literature presents different physical and empirical models to predict the thermal conductivity of the soil based on the soil characterization and its water content, but they are of difficult use due to the need of estimate additional coefficients for each constituent [15]. Moreover, the models are less effective in the case of low water content, which is the common state for RE walls (lower than 2-3%) [15,18]. To investigate further, some models for two-phase unsaturated phase media (Kersten, 1949 [15], Cosenza et al. [18]) were tested in the present case study, without obtaining a coherent result in the prediction of the thermal conductivity. In order to find a functional model for the specific application of RE, the range of investigation in the present study was limited only to RE materials. As already mentioned, different authors claim a linear relationship between the water content and the thermal conductivity for a given RE [4,15,19,20]. Therefore, a larger number of data from different soils were compared, plotting the thermal conductivity variations as a function of moisture content. Additional measurements of unstabilized RE materials from Chabriac [15], Tan et al. [21], Soudani [4] and Losini [22] have been included. Globally, the study includes measurements of 6 different RE, summarized in Table 1. Anyway, the number of compared soil is still limited due to the lack of available data in the literature and the decision to exclude from the study stabilized RE and other construction techniques.

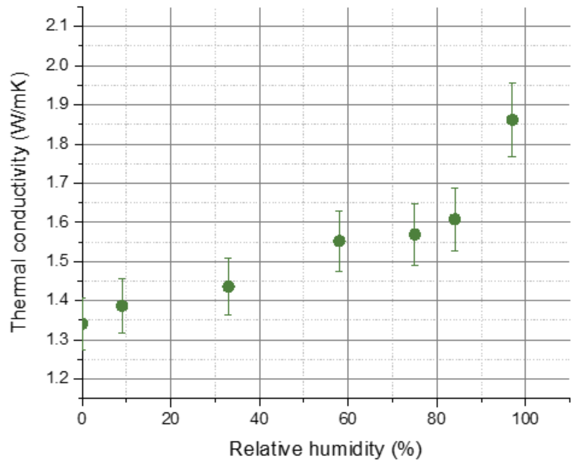

Fig. 4. Thermal conductivity for sampels at different RH%.

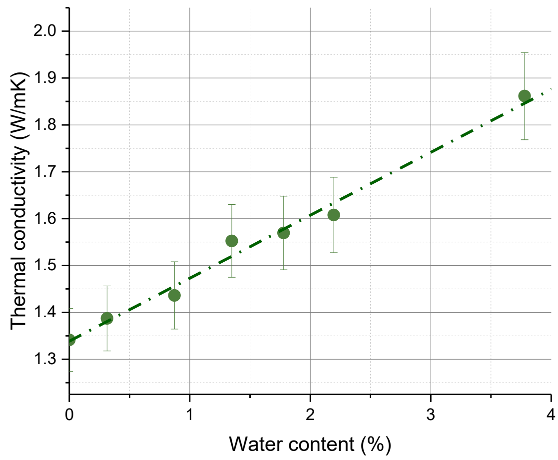

Fig. 5. Thermal conducitivty measured at different moisture content.

Fig. 6 reports measurements of thermal conductivity plotted against water content for 6 different RE. For each RE, λ_w shows a linear variation in the moisture content. A formulation cited by Soudani [4] [23] is here applied to describe the variation of thermal conductivity as a function of water content using an empiric model:

$$\lambda_w = \lambda_{dry} + C_s \cdot w \tag{3}$$

Where λ_{dry} is the dried thermal conductivity, w the moisture content and *Cs (-),* a constant dependant of the soil. Since it is not possible to predict the value of dry thermal conductivity as a function of its density, λ_{dry} needs to be experimentally determined. All 6 soils present a linear interpolation with a satisfying R^2 value, reported in Table 1. The coefficient C_s presents a variability between 0.086 and 0.14 for 5 out of 6 soils investigated (Table 1). The only exception is represented by the soil from Mianyang, China, from a study by Tan et al., with a C_s value equal to 0.03 [21].

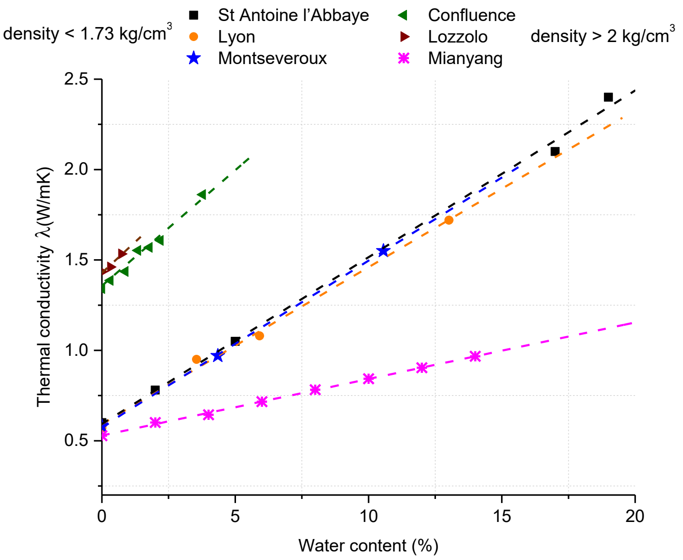

Fig. 6. Thermal conductivity against water content for six different soils.

This RE presents similar parameters to the other soil from Lozzolo [22] and Confluence, with a density of 2100 kg/m^3 and compressive strength of 2 MPa, while its thermal conductivity has different behavior. It increases from 0.528 at the dry state to only 0.967 for a water content near the liquid limit of the material. The different behavior of this soil may be due to the grain size distribution, but this information is missing in the article, only the maximal grain size is reported (2mm), the same of Lozzolo soil.

Table 1. Resume of RE Υ_d, n, λ_{dry}, C_s, R^2 and the reference.

RE	Υ_d (g/cm^3)	λ_{dry} (W/mK)	Cs (-)	R^2	Ref.
St Antoine	1.73	0.64	0.09	0.99	[4,15]
Lozzolo	2.1	1.44	0.14	0.93	[22]
Confluence	2.02	1.34	0.13	0.99	-
Lyon	1.62	0.57	0.09	0.99	[15]
Montrservoux	1.62	0.61	0.09	0.99	[15]
Mianyang	2.1	0.53	0.03	0.99	[21]

This result suggests the hypothesis that for a limited range of moisture content (0 to 20%), the variability of coefficient *Cs (-)* for RE materials may be approximated to a unique value for different types of RE materials, in this case estimated around 0.09-0.1. A larger batch of unstabilized RE analysis on the thermal conductivity should be investigated to confirm if this hypothesis can globally be adopted. We have seen that some earth does not follow this framework, as it is the case for Mianyang soil.

3.3 Conclusions

Considering the sorption desorption isotherm, the increment of hysteresis is lower than 0.26% when the material undergoes relative humidity lower than 84%, while for values around 98% of relative humidity, the hysteresis is more than doubled. The thermal conductivity λ increases by about +19% from 0 to 75% RH, while the highest increase occurs at 97% RH% up to +39% compared to λ_{dry}. Thanks to empirical relations of several earths, it is possible to linearize λ as a function of the moisture content w, given the dry thermal conductivity λ_{dry} (intercept) and the slope C_s, a coefficient characteristic of the soil. The prediction of C_s according to soil characterization requires further investigations due to the complexity and variability of earthen materials. Reducing the field of investigation to RE materials, a first approximation of C_s is presented. Nevertheless, further investigations on a larger batch of RE are required to generalize these analyses.

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