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Abstract. The rehabilitation of ancient rammed earth houses, as well as the use of earthen materials in modern constructions, are a growing matter of concern, especially in area such as Rhône-Alpes, France, where 40% of old constructions are in rammed earth. A current pathology observed for this type of construction is related to the rising damps, for which the water from the ground is absorbed by the wall. This situation leads to a very saturated state. As it has been proven that the compressive strength is altered by the presence of water in the pores, a better understanding on high relative humidity range is necessary to be able to predict the mechanical behavior of buildings and thus ensure a better risk assessment. The present study describes experimental results of the water uptake experiments and moisture storage at high relative humidities.

1. Introduction

Available everywhere in the world and used as a construction material for thousands years, raw earthen material can provide an answer to the world population construction needs, at an economic level as well as at an environmental one. However, it suffers from a poor scientific understanding as its knowledge is essentially practical, even though its behavior differs from other usual construction materials. As a consequence, it requires a wide range of measurements to describe its particular thermal, hydric and hygrothermal behavior. This goes from the material characterization to the full-size measurements, including wallet scale. In particular, earthen materials are able to hold a large amount of liquid water, compared to the other construction materials. A current pathology observed for this type of construction is related to the rising damps, for which the water from the ground, or massed at its surface, is absorbed by the wall. But, it has been proven that the moister the material is, the lower is its compressive strength [1], [2]. When those rising damps are too important, it thus can alter the whole building stability. Concerned about being able to assess how vulnerable a construction can be regarding to this type of pathology, studies are being carried out to characterize the capacity of this material to retain liquid water.

The water fills the pores of the material through its different states: liquid and vapor. The overall mass conservation of water (in both liquid and vapor) within a representative elementary volume of the material, and considering an isothermal case, can be written in the following form (see for example [3] for detailed derivation):

$$\frac{\partial w_L}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \boldsymbol{\nabla} \cdot \left(\delta_p \boldsymbol{\nabla} p_v + D_L \, \boldsymbol{\nabla} p_L\right) \quad (1)$$

Where w_L is the liquid water content, $\boldsymbol{\nabla}$ is the nabla symbol, p_v and p_L are respectively the partial pressure of vapor and the pressure of the liquid water, D_L is the liquid permeability, δ_p is the vapor transport coefficient, φ is the relative humidity. The right hand side of this equation refers therefore to

transfer phenomena, while the left hand side describes water sorption capacity. The latter can be described by the sorption isotherm (water content in function of relative humidity) and then the retention curve (water content as a function of suction, for high values of relative humidity).

The relation (1) underlines that two kinds of water transport occur within the material. The first one, detected by the term $\boldsymbol{\nabla} \cdot (\delta_p \boldsymbol{\nabla} p_v)$ corresponds to the flow of water vapor, while the second one, $\boldsymbol{\nabla} \cdot (D_L \boldsymbol{\nabla} p_L)$ is the transport of liquid water. When a large amount of liquid water is flowing through the material, the liquid transport is prevailing upon the water vapor diffusion.

Knowing the behavior of the material close to saturation is a matter of concern in two main cases. First, the manufacture requires a large amount of water to be added; the material is thus saturated when it has to bear all the dead loads[4]. Second, pathologies such as rising damps can drastically increase the water content which reaches values close to saturation. The stability of the whole structure can be at stake, hence the importance of a good characterization for a better predictability of collapses.

Specifically, the retention curve is needed in order to assess water storage capacity of material. It is based on the suction (or capillary pressure), which is the difference between the atmospheric and the liquid pressure, denoted by S. The relation between the capillary pressure and the water content can be measured through different methods, more or less accurate for different types of soils and pressure ranges. The document [5] provides a good overview of the common methods:

- The most spread technic, the tensiometric measurement consists in measuring the negative pressure of liquid water using a thin saturated porous stone. The range of practical application is for pressures between 0 and 80kPa.
- In psychrometric measurements, the relative humidity is measured close to the interstitial water of the non-saturated soil, from which is deduced the suction thanks to the Kelvin law. The relative humidity is calculated through the dew point temperature of the considered atmosphere. It is a quite sophisticated method and remains unusual. The pressures thus determined don't exceed 7 MPa.
- Filter paper method is a simple and convenient method to measure suction as it only requires a 1/10 000e weighting scale. It consists in using a filter paper whose retention curve was determined before, putting it in a sample and wait for equilibrium between the filter paper and the soil. After extraction, knowing the water content of the paper, and its retention curve, it leads to the suction of the soil. Depending on which type of filter paper is used, several calibration curve can be found in the literature [16]–[19].

The link between the suction curves and the sorption curves is eventually made through the Kelvin's law (chemical equilibrium between liquid water and its vapor):

$$S = p_0 - p_L = -\frac{\rho_L R T}{M_w} \ln \varphi \qquad (2)$$

with p_0 the atmospheric pressure, R the perfect gas constant, T the absolut temperature in K, M_w the molar mass of water molecules and φ the relative humidity.

Concerning transport properties, several authors have pointed out the practical troubles to measure the liquid water permeability of unsaturated soils, even if some experimental set up have been designed to overcome these difficulties [5]–[9]. Still, they remain quite sophisticated and not widespread.

Concerning earth-based materials, the use of the absorption coefficient, commonly called the A-Value, and defined by the total amount of water absorbed (in kg) per surface unit in contact with water (in meter square) and per square root of the immersion time (in seconds), is the most widespread

method. The protocol of measurement is provided by the European standard EN 1015-18. Its calculation is illustrated Figure 1. The standard deals with masonry mortar but the same procedure can be applied to other porous materials. The A-value is measured on prismatic samples of 0.80x0.40x0.40 m3, initially dry, and submerged in 5 to 10 mm of water for 90 minutes. Samples are weighted after 10 and 90 minutes and the absorption speed is deduced. The water level has to be constant during the measure and the sample shouldn't stand directly on the bottom of the tank but on wedges so that the whole lower surface can be in contact with water.

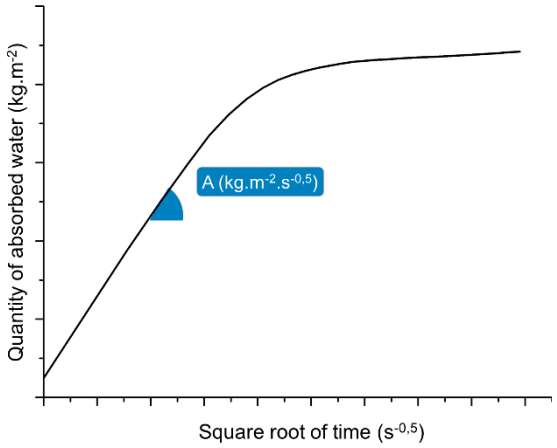

Figure 1: Calculation of the liquid absorption coefficient A

The British standard BS 3921 deals with measuring the capillary suction of water in building materials, and explains the specifications of the Initial Rate of Suction (IRS) test. The test is to be done on dry samples and weightings every minute during 5 min. However, some instructions aren't suitable for earthen materials. Hall [10] suggested another method, based on this standard. The measurement is made on cube samples of 10 cm. The samples are weighted at 1, 2, 3, 4, 5, 10, 20, 30, 40 and 60 min.

The study described in [11] consists in measuring the A-value for 15 clay brick samples. The samples are cylindrical with a diameter of 20 cm and between 1.5 and 2 cm thick. Each sample laid on a 1 cm thick paper saturated with distilled water at 20°C, put in a closed vessel to reach saturation conditions. Samples were weighted after 10, 20, 30 minutes and 1, 4, 6, 24, 48 and 72 hours.

In [12], the A-value, was determined according to the method described by Krus & Holm [13] and Hall [10] with the adaptation of the BS-3921 [14] standard to rammed earth. Indeed, some precautions need to be taken regarding the sensitivity of earth to water. In his PhD, Chabriac measured the A-value on compacted earth blocks of 0.295x0.14x0.10 m^3. The samples were weighted every 5 minutes for about one hour.

A more recent publication [15] studies the impact of stabilizers (lime, concrete) on the water transport properties. The liquid water absorption coefficient was measured on 3 types of rammed earth materials with different earth based mortars. The samples were cubic specimens of 50x50x50 mm^3 for mortars and blocs (30x20x28cm^3) and tested during around two days.

In this paper, the behavior of the material in high relative humidity range is investigated: first through suction measurements aiming at characterizing the sorption isotherm above 97% RH. Secondly, the liquid water absorption coefficient is derived from the water uptake experiment. The latter are performed for different densities and lime concentrations.

2. Material and methods

2.1. Raw earth description

The soil was extracted from a village located at less than 6km away from Saint-Antoine-L'Abbaye in Isère, France. At material scale, various measurements were made, among which the particle size distribution, given in Figure 2.

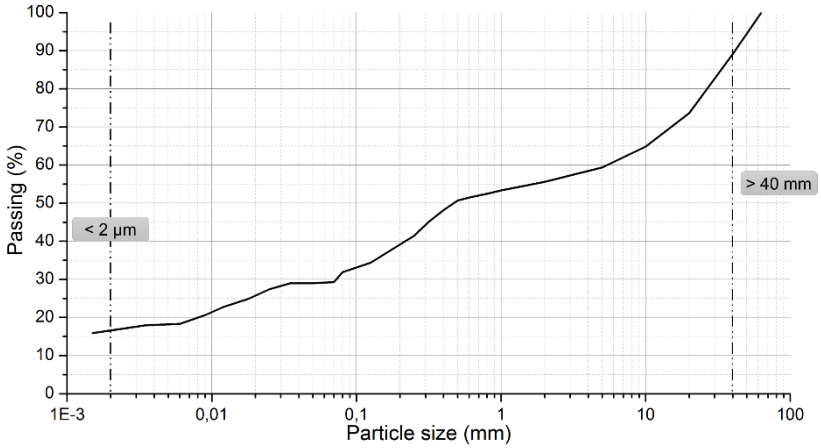

Figure 2 : Particle size distribution

It can be noticed that it includes around 10% of granulate with a diameter above 40 mm, typical of the houses of the area. The points below 2µm give the clay quantity, which reaches 16% for this material.

2.2. Definition of the lime content tested

Reference rammed earth constructions can be stabilized adding lime to the soil before compaction. The lime works on the clay minerals and can improve its strength against liquid water, particularly important for water uptake tests. The dosage is usually between 6% and 12% per dry weight and increases as the clay content increases [22].

In order to provide a better control of liquid water in the soil during construction, the natural soil was mixed with 2.5% of NHL5 lime, which represents a rather low quantity. In those conditions, the manufacturing moisture content was about 0.183 $kg.kg^{-1}$.

Samples with different lime percentages (0%, 2.5%, and 4%) were made and no curing period was considered. Indeed, lime chemically affects the soil only after a long period of time, which hadn't been waited for. In practice, the problem of liquid water migration raises starting from the construction, as a large amount of water is added. The early ages of the material are usually more affected and thus the object of following study.

2.3. Estimation of the accurate range of density variation

The dry density on site of the studied soil was measured on samples taken from a test wall realized before building the house, and was equal to 1,7. This density can be considered as low, in comparison to other modern rammed earth constructions (broad range of 1.7-2 [23]). An explanation can be the high built-in moisture content that prevents, up to a certain point, the compacting - the water being incompressible.

However, after the destruction of an experimental wallet, made by the same mason and with the same material, occurring about one and a half year after its construction, the density was measured at different spots. No regular distribution was found, nevertheless about 90% of the 23 studied samples had a density ranging from about 1.5 to 1.8. It has thus been decided to work on samples with different densities in that range.

2.4. Sample preparation and conditioning

The shape of the sample was chosen with a penetration surface wide enough in order to enable the rising damp phenomenon. The Proctor type samples were prepared: cylinders with a diameter of 10 cm and a height of approximately 6 cm. In these conditions, the penetration surface (bottom of the cylinder) was 7.85 cm^2. The soil with lime to be added was prepared about one hour before compaction, as advised in the standard EN 1015-18. In order to obtain the sample as homogenous as possible, the soil was compacted in one layer, and the on-site density of 1.7 was sought. The manufacturing of the samples is illustrated in Figure 3.

Figure 3 : Manufacturing the samples

3. Results and discussion

3.1. Sorption isotherms and retention curves

3.1.1. Sorption-desorption isotherms

Sorption/desorption were determined in a previous study [12] using saturated salt solutions and performed at 20°C. The results are given in Figure 4. As for all earthen materials, the slope of the isotherms in the high relative humidity is very important, which shows the high ability of this type of material to adsorb and hold water.

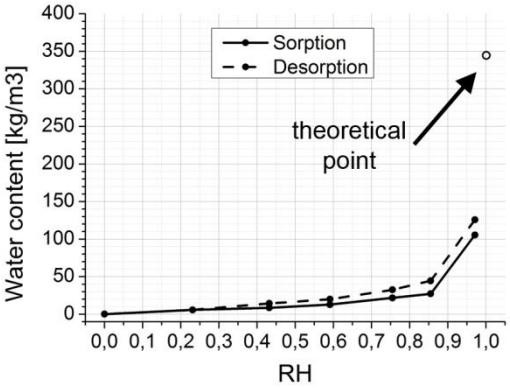

Figure 4 : Moisture storage curves in sorption and desorption

The measurement of sorption-desorption curves through salt solutions or gravimetric dynamic sorption analyzers at relative humidity higher than 95% is quite inaccurate. In addition, these methods cannot reach the saturated state, and the point RH=100% must be obtained theoretically (from the porosity). Consequently, the use of the sole sorption-desorption curves leads to high uncertainties in the range between 95% and 100% of relative humidity.

Therefore, for the suction curve, the filter paper method was chosen and the practical protocol is described in the standard [18].

3.1.2. Evolution of water content in the capillary domain

The experimental investigation was divided into two parts: the calibration of the filter paper and the suction measurement in the studied soil. Since many different calibration curves for the paper Whatman n°42 can be found, depending on the environment and other parameters, the calibration of the filter paper used was realized in the laboratory, but not detailed in the following.

The suction curves were measured on cylindrical samples of 15.2cm of diameter, and two layers of 1cm thick. They were manufactured with the studied soils at different mass water content (4%, 8%, 12%, 15% and 18%) with four samples each. Three filter papers, dried before, were put in-between the two rammed earth layers during manufacture, the one in the center having a diameter about 5mm below the two others to prevent it from soil contamination. The sample was then sealed with a plastic film and stored in a room with controlled indoor temperature and relative humidity for 7 days. The samples were weighted before and after the equilibrium period to ensure the correct sealing. After that period, the samples were destroyed with care to extract the central filter paper and retrieve its mass. The dry mass being measured previously, for each water content of the soil the corresponding mass water content of the filter paper was obtained.

Figure 5 : Suction measurement on earthen cylindrical samples

Thanks to the calibration curve of the filter paper, the retention and then the sorption isotherm could be deduced. They are both gathered in Figure 6 .

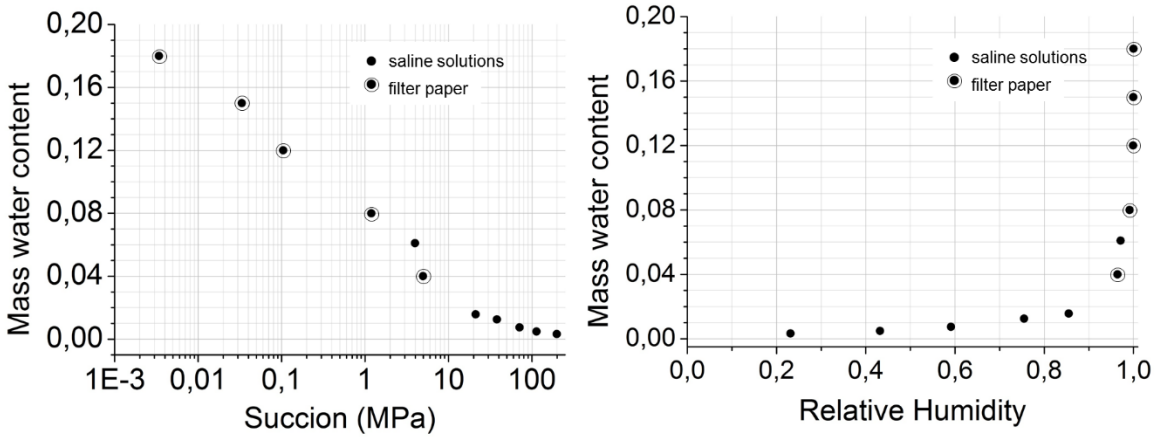

Figure 6: Final retention curve and sorption isotherm at 20°C

A good correlation can be observed between the “saline solution” data and the one measured with the filter paper. It then appears that these two methods complement one another to describe the behavior of the soil in both hygroscopic and capillary domains.

3.2. Liquid water uptake test

3.2.1. Test principle

The aim of this test is to measure the rising of water by capillarity. To ensure a one dimensional transport of liquid water, the lateral surfaces of the samples were sealed with paraffin and foil, as can be seen in Figure 7.

Figure 7 : Sealing the lateral faces

The device used for the measurement of liquid absorption coefficient was composed by a tank filled with water and a grid on wedges. Tea filter papers were added between the sample and the grid so that the tiny particles of earth didn't go in the water as the sample was becoming wet, as described in [12]. The samples were put on the grid and the grid on the water. After a certain time (shorter periods of time in the beginning and increasing), the grid was taken off and weighted. Care was taken not to keep water on the grid that wasn't absorbed by the sample, and the grid was wiped out carefully when necessary. After the weighting (happening within 30 seconds), the grid was put back on the edges and the capillary absorption could go on.

Questions have been raised concerning the time to be considered. Several references ([20], [21]) highlight the fact that the weighting operation has to be done as quick as possible. However, the time considered was strictly the time during which the sample was absorbing water, i.e. every weighting times were deleted from the whole time measurement.

The tests were realized in a room where the relative humidity nor the temperate were controlled. Therefore, to ensure a better understanding of the results, the temperature and relative humidity were measured with a USB sensor (EL-USB-2, Lascar electronics, Salisbury, UK).

3.2.2. Results

Twelve samples were tested for different densities and lime contents. The characteristics of the 12 samples are reported in Table 1.

Table 1: Densities and lime content of tested samples together with ambient temperature and relative humidity during test.

Lime	**0%**				**2.5%**				**4%**			
Name	0A1	0A2	0B1	0B2	25A1	25A2	25B1	25B2	4A1	4A2	4B1	4B2
Density	1.59	1.58	1.62	1.67	1.44	1.47	1.71	1.67	1.57	1.53	1.65	1.68
T [°C]	25.3	25.0	25.8	24.0	23.3	24.1	29.5	29.5	23.5	24.6	24.2	24.5
RH [%]	39	39	38	53	47	44	44	44	42	40	54	55

The experiment enabled us to measure the total amount of water absorbed in the sample divided by the surface area, against the square root of time. The cinematic of the rising water was measured and is synthesized in Figure 8, respectively for 0%, 2.5% and 4% of lime. Each of these graphs compare the

results for samples of different densities for the same percentage of lime. They also include the linear regression for each case: the A-value (slope) and the R^2.

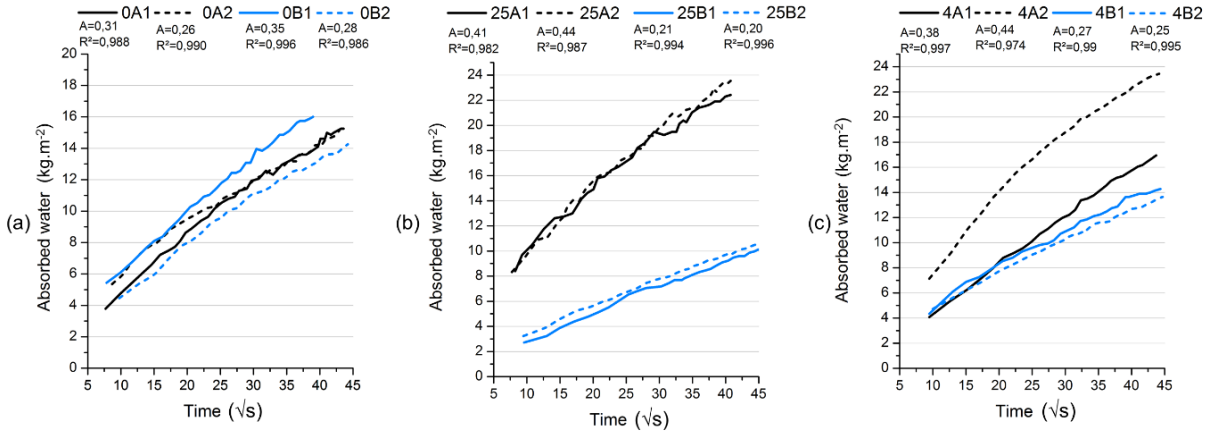

Figure 8 : Comparison of samples for three lime contents and different densities (a) 0% of lime; (b) 2.5% of lime; 4% of lime

The
Table ***2*** provides the A value for all samples, depending on the presence of lime or not.

Table 2: A value for each sample

Lime	0%				2.5%				4%			
Name	0A1	0A2	0B1	0B2	25A1	25A2	25B1	25B2	4A1	4A2	4B1	4B2
Density	1.59	1.58	1.62	1.67	1.44	1.47	1.71	1.67	1.57	1.53	1.65	1.68
A	0.31	0.26	0.35	0.28	0.41	0.44	0.21	0.20	0.38	0.44	0.27	0.25

For all cases, the linearity of the relation between the two parameters (absorbed water and square root of time) can be noticed. Observing a straight line (R^2 always above 97%), the liquid water absorption coefficient, which is the slope of this line, could be deduced without any trouble.

In the case of 0% lime, the curve of samples (0A1) and (0A2) are very similar, which provides a good repeatability for the measures. On the other hand, the behavior of samples (0B1) and (0B2) is slightly different: the differences in the relative humidity of the environment during the measure can be an explanation.

In the case of 2.5% lime, both the good repeatability and the difference between densities can be easily observed.

At last, the results when there is 4% lime somehow different from the previous ones: for the samples (4B1) and (4B2), the repeatability is good but, not for the samples (4A1) and (4A2) even if the slope of the curve and thus the coefficient needed is close. However, the gap between the two last samples seems to be created during a transient regime occurring in the first moment when the material is dry and isn't representative of its behavior when saturated with water.

Link with density: The first observation of this experimental campaign is the relation between the density and the A-value. All the measurements are gathered in Figure 9.

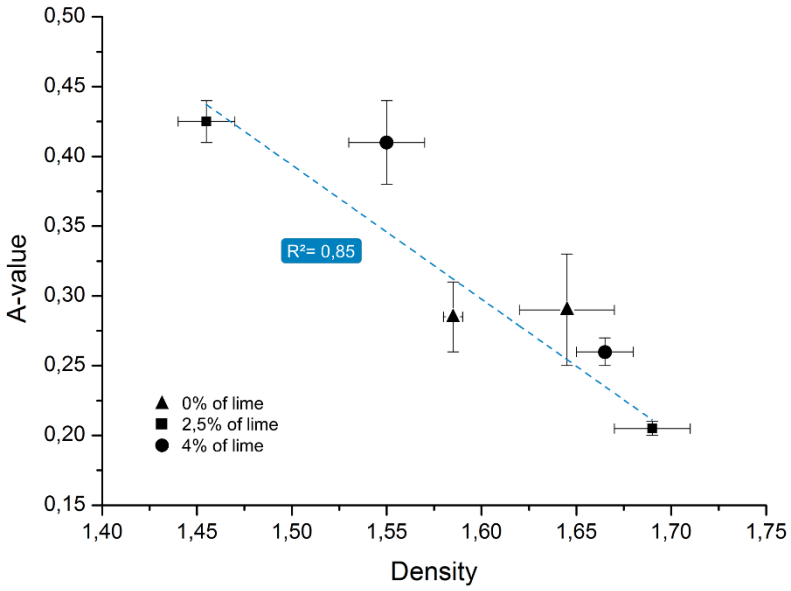

Figure 9: Comparison of A-value for different densities and lime concentrations, with their respective standard deviation

This figure shows that the A-value decreases as the density increases, which is quite intuitive. What's more, there seems to be a linear correlation between the density and the A-value, with a correlation coefficient equal to 0.85.

Link with lime concentration: The last conclusion is the fact that no significant differences are observed in terms of lime concentration variation. It seems that the quantity added doesn't impact the transport of liquid water. However, as mentioned before, the tests were done at early age of samples, therefore the chemical processes due to lime did not occur before testing. After several months, this chemical reaction might have a larger effect, as shown in [15].

4. Conclusion

To conclude, the measurement of the liquid absorption coefficient is a relatively easy-to-perform experiment, as far as a study of the possible influences (surrounding atmosphere, sealing, etc.) on the results is carried out and that the testing is conducted with care. Using filter paper to assess suction curve requires preliminary calibration of the paper, and then careful manipulations. Both tests provide interesting data to assess rammed earth behavior at high relative humidities. In addition, at early age of the samples the addition of lime was found to have no significant impact on liquid uptake.

As the next steps of this work, numerical behavior of samples will be modelled. Moreover, additional tests will be conducted in order to assess the impact of air pressure on capillary transport.

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