The effect of ambient humidity on the stiffness and strength of a hyper-compacted silty clay for earth building

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ABSTRACT: The effect of pore suction and water content on the engineering properties of partially saturated soils has been extensively studied by geotechnical researchers. It is well known that unsaturated soils become stiffer, stronger and less permeable as suction increases and saturation decreases. The results from these studies are however not directly applicable to the analysis of earth buildings, which are made of coarser soils compacted to a much denser state. The present paper investigates the mechanical behaviour of a low porosity earth building material equalised at different degrees of saturation. Cylindrical samples were statically compacted to a high pressure of 100 MPa at the optimum water content. This resulted in a dry density of about 2.3 g/cm^3, corresponding to a porosity of between 13% and 14%, which is uncommonly low for standard geotechnical materials. After compaction, the samples were equalised at different humidity levels inside a climatic chamber before being subjected to triaxial tests under different confinement. Results from these tests enabled the definition of the material stiffness and strength envelopes at different levels of ambient humidity.

1 INTRODUCTION

Modern construction standards promote the use of sustainable materials that reduce carbon emissions and energy consumption throughout the lifetime of buildings (e.g. Morel et al., 2001). Among these materials, raw earth is one of the most promising options (Gallipoli et al., 2017). The expression "raw earth" indicates a construction material consisting of a compacted mix of soil and water, which is put in place with the least possible transformation (Jaquin et al., 2009). Because of its hydrophilic nature, raw earth exhibits a strong tendency to adsorb or release moisture, and therefore to emit or store latent heat, depending on current levels of ambient humidity. This property helps to regulate the variation of relative humidity and temperature inside dwellings, thus contributing to the health and comfort of occupants (Pacheco-Torgal and Jalali, 2012) while increasing energy efficiency.

Global warming is likely to produce a significant change of climate over future years with drier summers, wetter winters and stronger storm events. Buildings will therefore be subjected to larger humidity excursions, which will produce greater variations of pore water inside exposed materials with potentially important consequences on structural serviceability. Geotechnical researchers have already shown that the stiffness and strength of clayey soils reduce as saturation increases and suction drops. These results are however not directly applicable to earth buildings which are made of coarser, i.e. silty and sandy, materials. Moreover, unlike most soils investigated by geotechnical engineers, the materials encountered in earth buildings are compacted at high densities and therefore exhibit very low porosities.

The purpose of this paper is to investigate the mechanical behaviour of a hyper-compacted silt material with a very high density that is representative of earth buildings. The stiffness and strength of this material are measured by means of triaxial tests performed on samples equalised at different levels of humidity corresponding to different degrees of saturation. The effect of humidity is described by defining the strength envelope in the q:p plane (where q is the deviator stress and p is the mean stress) and the stiffness envelope in the E:p plane (where E is the Young's modulus).

2 MATERIALS AND METHODS

2.1 *Soil type and index properties*

The earth investigated in this work has been provided by the Bouisset brickwork factory from the region of Toulouse in France. Previous mineralogical studies of the Bouisset soil (Tercruso, 2013) have indicated a predominance of Kaolinite clay. Clay mineralogy is an important element to consider for earth buildings, whose hydro-mechanical behaviour is significantly influenced by the nature of the clay fraction. “Two-layer” clays, such as Kaolinite, are characterized by a relativity low specific surface (10 m^2/g) and therefore exhibit limited swelling/shrinkage upon wetting/drying. This makes these materials particularly suitable for earth construction.

The determination of plasticity and grading properties, is of primary importance to assess the suitability of earthen materials for building applications. In general, inorganic clays of medium to low plasticity are considered suitable for all earth construction techniques.

In this work, the plasticity properties of the fine fraction (i.e. the fraction smaller than 0.400 mm) of the Bouisset soil have been measured in agreement with the French norm AFNOR (1993). The liquid limit, plastic limit and plasticity index have been determined as the average of four independent tests. Figure 1 shows the plasticity characteristics of the Bouisset soil with reference to the Casagrande chart, which indicates that this material can be classified as a low plasticity clay. Figure 1 also shows the admissible regions for the manufacture of compressed bricks according to Houben and Guillaud (1994) and AFNOR (2001); CRATerre–EAG (1998), respectively. These admissible regions were taken from the work of Delgado and Guerrero (2007), who reviewed more than 20 technical documents including national standards to define general guidelines for earthen construction. The two admissible regions shown in Figure 1 are those relevant to the manufacture of earth bricks and confirm the suitability of the Bouisset soil for this particular building technique.

The grain size distribution is another important parameter for assessing the suitability of earthen materials for construction. In the present work, the grading curve has been determined by means of wet sieving and sedimentation tests in compliance with the norms AFNOR (1995) and AFNOR (1992). The measured curve is shown in Figure 2, which also presents the lower and upper limits recommended by AFNOR (2001); CRATerre-EAG (1998) and MOPT (1992) for compressed earth bricks. Inspection of Figure 2 indicates that the grain size distribution of the Bouisset soil lies close to the fine limit of current recommendations. Again, the admissible regions shown in Figure 2 were taken from the review of Delgado and Guerrero (2007) and are relevant to the manufacture of earth bricks.

Finally, the specific gravity of the solid particles has been measured by means of pycnometer tests according to the French norm AFNOR (1991). Table 1 summarises all measured properties, which indicate that the Bouisset soil can be classified as a well graded silty clay.

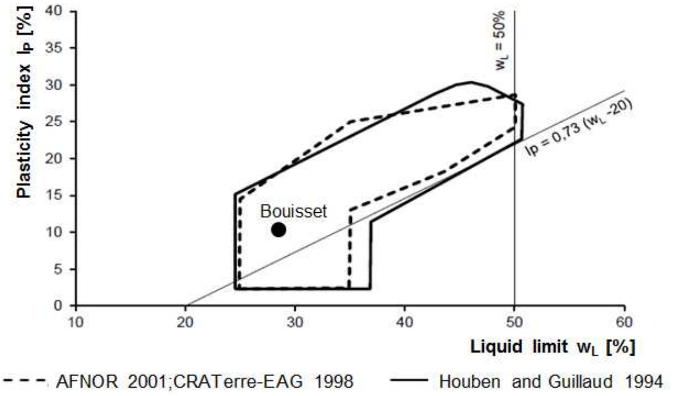


Figure 1. Plasticity properties of Bouisset soil in relation to recommendations for the manufacture of compressed earth bricks by AFNOR (2001); CRATerre-EAG (1998) and Houben and Guillaud (1994).

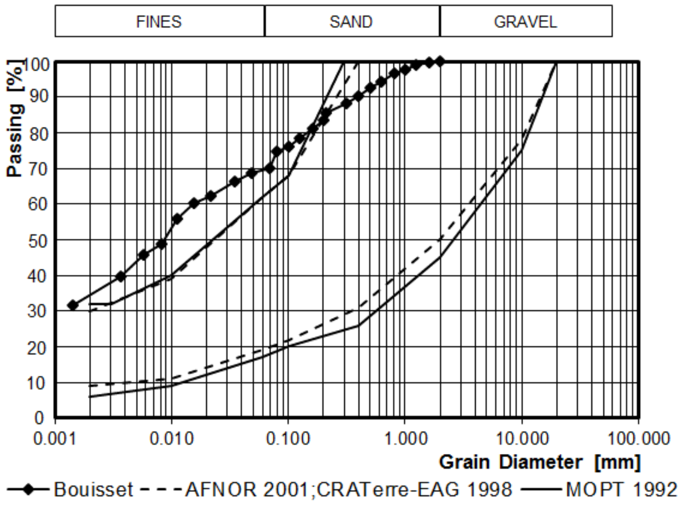


Figure 2. Grain size distribution of Bouisset soil in relation to recommendations for the manufacture of compressed earth bricks by AFNOR (2001); CRATerre-EAG (1998) and MOPT (1992).

Table 1. Measured index properties.

Index property	
Proctor standard compaction tests	
Maximum dry density (g/cm^3)	1.97
Optimum moisture content (%)	12.4
Grain size distribution	
Gravel content (> 2 mm, %)	0
Sand content (≤ 2 mm, %)	31
Silt content (≤ 63 µm, %)	35
Clay content (≤ 2 µm, %)	34
Specific gravity	2.65
Atterberg limits	
Plastic limit (%)	18.7
Liquid limit (%)	29.0
Plasticity index (%)	10.3

2.2 *Sample properties and compaction method*

The compaction curve of the Bouisset soil was determined for two distinct efforts corresponding to static hyper-compaction at 100 MPa and the standard Proctor (AFNOR, 1999), respectively. The term "hyper-compaction" refers to the application of a pressure significantly higher than that applied during production of conventional earth bricks, which typically does not exceed 10 MPa. A considerable number of studies have analysed the influence of compaction effort on the mechanical properties of earthen materials (e.g. Bruno et al., 2016). In general, a higher compaction effort increases dry density and consequently stiffness and strength, thus resulting in mechanical characteristics similar to those of conventional building materials. A high compaction effort also reduces the variability of properties between specimens, thus facilitating quality control of the material.

Prior to compaction, the dry soil was mixed with the desired amount of water and subsequently placed inside three plastic bags to prevent evaporation. After that, the wet soil was left to equalize for at least one day so that moisture could redistribute prior to compaction.

Proctor samples were compacted according to standard procedures (AFNOR, 1999). In the case of hyper-compaction to 100 MPa, the soil was instead placed inside a stiff cylindrical steel mould with a diameter of 50 mm and vertically compacted by using a load-controlled Zwick press with a capacity of 250 kN. Pressure was applied by two cylindrical aluminium pistons acting at the top and bottom extremities of the specimen. This double-piston compression reduces the friction between the mould and the sample, thus increasing the uniformity of stresses inside the soil. Eight longitudinal fine grooves were cut on the outer surface of the pistons and the inner surface of the mould to facilitate drainage of pore air and pore water during compaction. Additional details about the compaction procedure are available in Bruno et al. (2016).

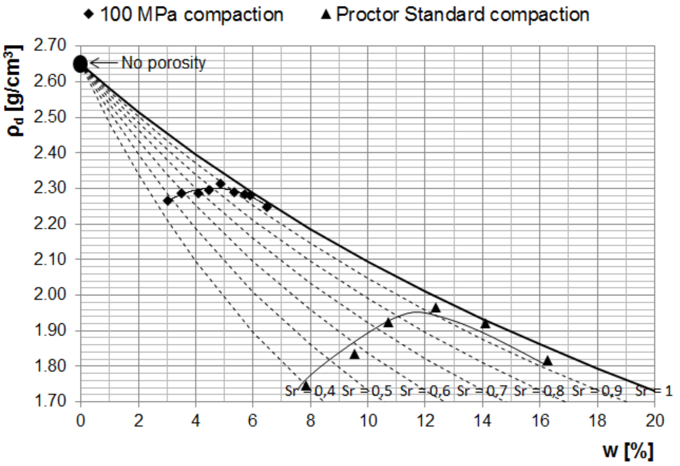


Figure 3. Compaction curves for the standard Proctor effort and a static pressure of 100 MPa.

Figure 3 presents the experimental values of dry density, ρ_d plotted against the corresponding water contents, w for both compaction efforts together with the respective interpolating curves. The increase of compressive energy from standard Proctor to 100 MPa produces a shift of the compaction curve towards the higher density range while the optimum water content becomes considerably smaller. Figure 3 also shows the theoretical ''no porosity'' point corresponding to an extremely high compaction effort, which produces a dry density equal to the density of the solid particles (i.e. 2.65 g/cm^3 as reported in Table 1). The optimum water content of the compaction curve at 100 MPa was found to be 4.88% corresponding to a maximum dry density of 2.31 g/cm^3 (i.e. a porosity of about 13%).

2.3 *Test setup and experimental program*

Fluctuations of ambient humidity induce changes of moisture content inside earth materials and affect the inter-particle bonding generated by capillary water. This in turns influences the strength and stiffness of the material (Jaquin et al., 2008).

To investigate this aspect, triaxial compression tests were performed on cylindrical samples hyper-compacted to 100 MPa at the optimum water content of 4.88%. Small cylindrical samples of 50 mm of diameter and 100 mm high were preferred to large bricks to avoid sharp corners that could induce stress concentration during fabrication and testing. An aspect ratio of 2 was chosen to limit the confining effect caused by friction between the sample extremities and the press plates during mechanical tests.

Distinct sets of samples were equalised inside a climatic chamber at a constant temperature of 25 °C but different levels of relative humidity, namely 25%, 62%, 95%. Samples were weighted every day and equalisation was assumed to be complete when the mass of the sample changed less than 0.1% over at least one week (that took generally 15 days).

The relationship between total suction, s at equilibrium inside the sample and the relative humidity of the surrounding air, RH is given by Kelvin's law:

$$s = \frac{\rho_w \, R \, T}{M_w} \ln RH \qquad (1)$$

where R is the constant of perfect gases (R=8.3145 J/mol·K), T is the temperature, M_w is the molar mass of water (M_w=0.018 kg/mol) and γ_w is the bulk density of water (γ_w=997.048 kg/m^3). For a temperature of 25 °C, it is therefore possible to calculate the imposed values of total suction from the relative humidity through Equation 1 (Table 2). Additional measurements could be performed in the future to better define the water retention curve of the material.

Another set of samples was also placed inside an oven for three days at a temperature of 105 °C to test material behaviour under dry conditions.

Table 3 summarizes the average values of bulk density ρ_b, water content w, degree of saturation Sr and porosity n measured after equalisation for all samples.

Table 2. Total suction after equalization at different humidity levels.

	s [MPa]
RH = 25%	190.1
RH = 62%	65.5
RH = 95%	7.034

Table 3. Samples properties after equalisation.

	ρ_b [g/cm^3]	w [%]	ρ_d [g/cm^3]	Sr [%]	n [%]
Dry	2.28	0	2.28	0	14.1
RH = 25%	2.31	0.683	2.29	11.7	13.4
RH = 62%	2.33	2.24	2.28	36.7	13.9
RH = 95%	2.38	4.61	2.28	74.9	14.0

After equalisation, samples were subjected to triaxial compression to measure both stiffness and strength under different levels of radial confinement. Tests were performed inside a conventional triaxial cell with a constant axial displacement rate of 0.06 mm/min while the back pressure line was open to atmosphere. To explore the effect of material confinement inside thick earthen walls, samples were tested at three different confining pressures of 0, 300 and 600 kPa. During compression, the exchange of moisture between the sample and the atmosphere through the back pressure line was considered negligible and the sample water content was assumed constant. Shearing was continued until failure and, in particular, until the identification of the peak deviator stress, which generally took between 23 and 35 minutes depending on the test. The results from triaxial tests were subsequently processed to determine the variation of stiffness and strength with confining pressure at each humidity level, as discussed in the following section.

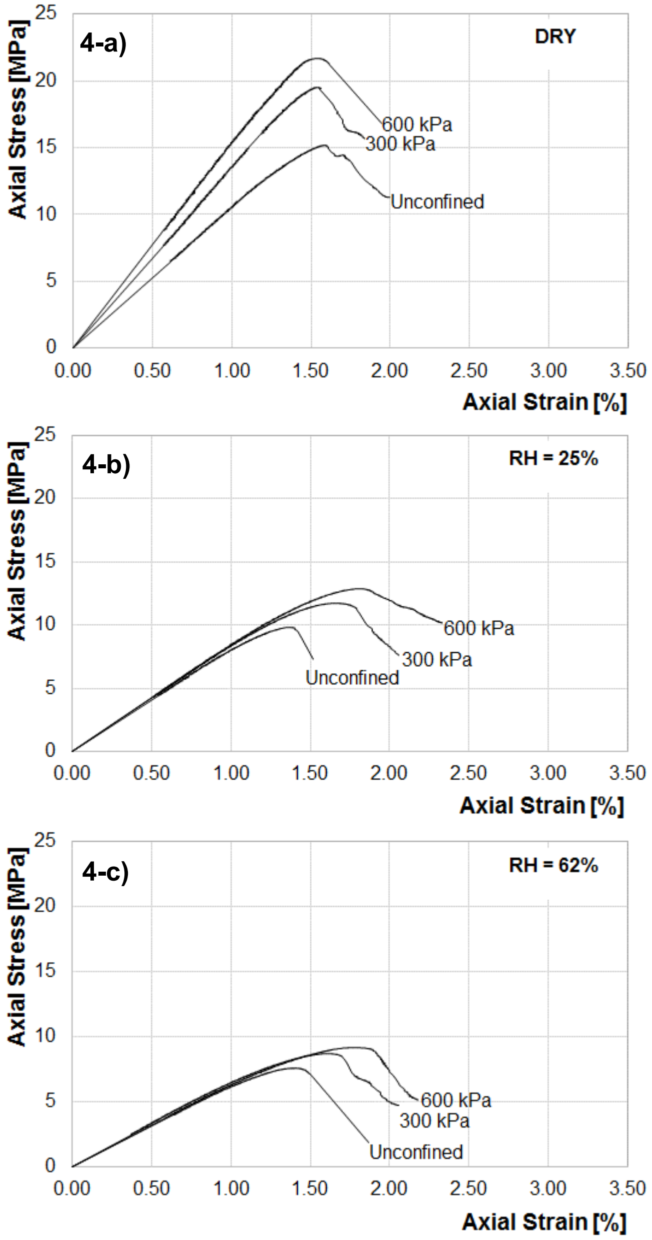
3 RESULTS

Figure 4 shows the stress-strain curves measured during triaxial tests at different confining pressures performed on samples equalized at different humidity levels. Inspection of Figure 4 indicates that, as expected, peak strength increases when confining pressure increases regardless of the humidity level at which samples were equalised.

Moreover, the peak stresses at a given confining pressure increase as humidity decreases, which provides further evidence of the link between water content and strength. This result corroborates the assumption that, in unsaturated conditions, capillary menisci bond particles together, thus improving the mechanical characteristics of the material (Beckett and Augarde, 2012).

The highest values of strength were measured on dry samples, for which the peak stress attained values greater than 20 MPa. If the samples were indeed dry, no capillary menisci should however be present and the strength should be the lowest one. This is because a dry material is conceptually no different from a saturated one for which the principle of effective stresses applies. The explanation of this apparent contradiction might be that the oven-dried sample is in fact not completely dry and a small quantity of adsorbed or capillary water still exists under very high tension, thus continuing to bond particles together. This is an aspect that requires further investigation.

Inspection of Figure 4 also indicates that the mechanical behaviour changes from fragile to ductile as humidity increases. Therefore, an increase of water content reduces shear strength but also improves the ability of the material to undergo significant plastic deformation before failure.



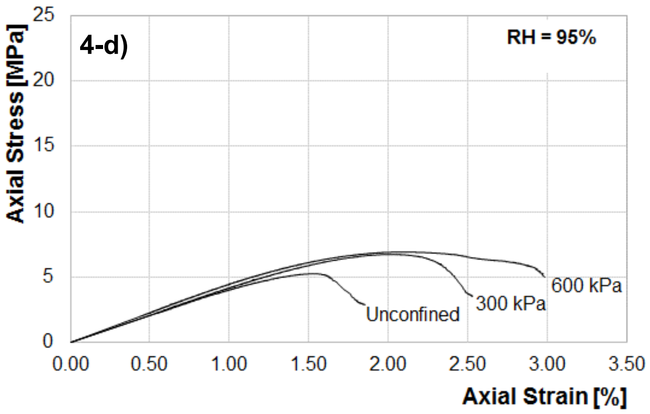


Figure 4. Stress-strain curves: results from triaxial tests at different confining pressures for distinct levels of humidity: dry (Fig.4-a), 25% (Fig.4-b), 62% (Fig.4-c), 95% (Fig.4-d).

Figure 5 shows the peak values of deviator stress q measured at the three different confining pressures and plotted against the corresponding values of mean stress p for all four humidity levels. The four interpolating lines are described by the general equation:

$$q = C + (M\,p) \qquad (2)$$

where the coefficients C and M are respectively the intercept and slope of the failure envelope. These coefficients can be converted into corresponding values of cohesion c and friction angle φ by means of the following equations:

$$M = \frac{6\,sin\varphi}{3 - sin\varphi} \quad \rightarrow \quad sin\varphi = \frac{3\,M}{6 + M} \qquad (3)$$

$$C = \frac{6\,c\,cos\varphi}{3 - sin\varphi} \quad \rightarrow \quad c = \frac{(3 - sin\varphi)\,C}{6\,cos\varphi} \qquad (4)$$

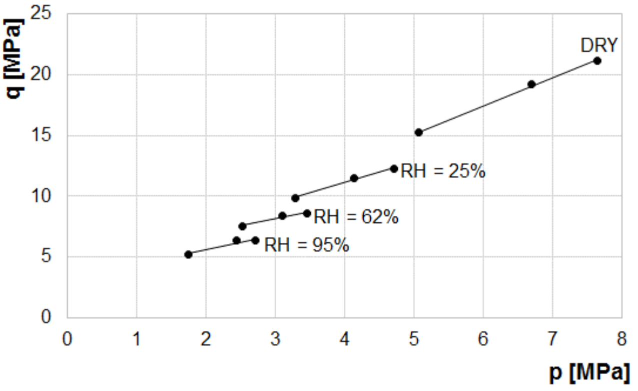


Figure 5. Peak strength at different confining pressures and humidity levels.

Table 4 summarises the strength parameters measured on all samples and indicates that cohesion remains approximately constant at different humidity levels while the friction angle increases considerably as the material is exposed to a drier atmosphere and water content decreases. A slight deviation from this trend is noticed for the samples equalised at the highest humidity of 95%, which is probably due to the greater measurement scatter of these samples.

Table 4. Strength parameters for samples equalised at different humidity levels.

	M *[-]*	*φ* *[°]*	*C* *[MPa]*	*c* *[MPa]*
Dry	2.31	56.6	3.53	2.31
RH = 25%	1.74	42.3	4.20	2.20
RH = 62%	1.12	28.2	4.77	2.28
RH = 95%	1.24	30.8	3.15	1.52

Figure 6 shows the variation of the Young's modulus E with mean stress p at all four humidity levels. The Young's modulus is equal to the initial slope of the axial stress-strain curves presented in Figure 4 measured over the stress range where the material response is reasonably linear. Inspection of Figure 6 indicates that the Young's modulus decreases with increasing ambient humidity as a consequence of growing water content. The confining pressure exhibits a marked influence on Young's modulus only for samples tested in dry conditions while the effect is significantly smaller in the other cases.

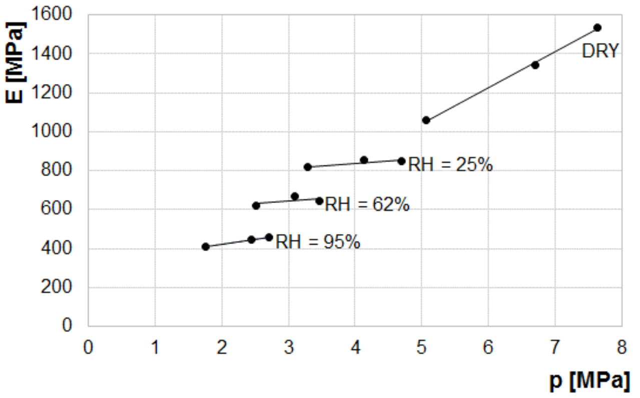


Figure 6. Young's modulus at different confining pressures and humidity levels.

4 CONCLUSIONS

Earth is a promising construction material for improving the sustainability of buildings as it can significantly reduce current levels of embodied and operational energy. In order to overcome the empiricism that characterises the design of earth structures, some methods and models presently used by geotechnical engineers could be usefully exploited (Gallipoli et al., 2014; Jaquin et al., 2008). Likewise unsaturated soils, earth building materials are characterized by the presence of meniscus water bridges between particles, which generate capillary bonding and increase strength and stiffness.

This paper has shown that the mechanical characteristics of hyper-compacted raw earth tend to improve as ambient humidity reduces and the degree of saturation decreases leading to an increase of inter-particle capillary menisci. At the same time, the ductility of the material (i.e. the ability to undergo significant plastic deformation before failure) tends to decrease as the material becomes drier. This sensitivity of mechanical characteristics to ambient humidity means that variations of moisture content should be carefully considered during design, construction and service life of earth buildings.

The paper has also shown that oven-dried samples exhibit the highest levels of strength and stiffness despite, in this case, capillary menisci should be absent and mechanical properties should therefore be relatively poor. Strength and stiffness are expected to peak somewhere between fully dry and saturated conditions when the bonding action of capillary menisci is most intense. A possible explanation of this apparent inconsistency may reside in the fact that the water content of the oven-dried samples is not zero, as commonly assumed, and that a small quantity of adsorbed and capillary water is still present, thus generating a suction inside the material. A truly dry material is a material saturated by air, which is conceptually no different from a material saturated by water, and should therefore obey the principle of effective stress. To further explore this aspect, additional tests will be performed on water saturated samples to compare the results with those presented in this paper for oven-dried samples.

Future investigation will also focus on the influence of particle size on strength and stiffness.

5 REFERENCES

AFNOR 1991. NF P 94-054; Soils: investigation and testing – Determination of particle density- Pycnometer method.

AFNOR 1992. NF P 94-057. Soils: investigation and testing – Granulometric analysis – Hydrometer method.

AFNOR 1993. NF P 94-051; Soils: Investigation and testing – Determination of Atterberg's limits – Liquid limit test using Casagrande apparatus – Plastic limit test on rolled thread.

AFNOR 1995. XP P 94-041. Soils: investigation and testing – Granulometric description – Wet sieving method.

AFNOR 1999. NF P 94-093. Soils : Investigation and testing — Determination of the compaction characteristics of a soil — Standard Proctor test — Modified Proctor test.

Beckett, C. T. S., & Augarde, C. E. 2012. The effect of humidity and temperature on the compressive strength of rammed earth. In *Proceedings of 2nd European Conference on Unsaturated Soils*:287-292. Naples, Italy, Springer, ISBN: 978-3-642-31342-4

Bruno, A. W. 2016. Hydro-mechanical characterisation of hypercompacted earth for sustainable construction. PhD Thesis, Université de Pau et des Pays de l'Adour.

Bruno, A. W., Gallipoli, D., Perlot, C., & Mendes, J. 2016. Effect of very high compaction pressures on the physical and mechanical properties of earthen materials. In *E3S Web of Conferences* 9:14004. EDP Sciences.

CRATerre-EAG 1998. CDI, Compressed earth blocks: Standards – Technology series No.11. Brussels: CDI.

Delgado, M. C. J., & Guerrero, I. C. 2007. The selection of soils for unstabilised earth building: A normative review. *Construction and building materials*, 21(2), 237-251.

Gallipoli, D., Bruno, A. W., Perlot, C., & Mendes, J. 2017. A geotechnical perspective of raw earth building. *Acta Geotechnica*, 12(3), 463–478.

Gallipoli, D., Bruno, A. W., Perlot, C., & Salmon, N. 2014. Raw earth construction: is there a role for unsaturated soil mechanics. In *Proceedings 6th International Conference on Unsaturated Soils* (pp. 55-62). Sydney, Australia, 2-4 July 2014, CRC. Press, ISBN: 978-1-138-00150-3

Jaquin, P. A., Augarde, C. E., Gallipoli, D., & Toll, D. G. 2009. The strength of unstabilised rammed earth materials. *Géotechnique*, 59(5), 487-490.

Jaquin, P. A., Augarde, C. E., & Legrand, L. 2008. Unsaturated characteristics of rammed earth. In *First European Conference on Unsaturated Soils*: 417-422). Durham, England, June 2008, Taylor & Francis Group, London, ISBN 978-0-415-47692-8

Morel, J. C., Mesbah, A., Oggero, M., & Walker, P. 2001. Building houses with local materials: means to drastically reduce the environmental impact of construction. *Building and Environment*, 36(10), 1119-1126

Pacheco-Torgal, F., & Jalali, S. 2012. Earth construction: Lessons from the past for future eco-efficient construction. *Construction and building materials*, 29, 512-519.

Tercruso 2013. Caractérisation des briques de terre crue de Midi-Pyrénées.

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