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ABSTRACT: This paper presents an investigation of the mechanical properties of three different earth building materials manufactured by compacting two soils with distinct particle size distributions under two markedly different efforts. Multiple samples of each material have been equalised either inside a climatic chamber at different humidity levels or oven-dried, before being subjected to shearing inside a triaxial cell to measure the corresponding levels of strength and stiffness. Triaxial shearing has been performed under different levels of radial stress to investigate the effect of material confinement inside thick walls. Consistent with previous research, the study has indicated that strength and stiffness increase as ambient humidity reduces and degree of saturation decreases, though the actual variation of these properties strongly depends on the dry density and clay content of the material. Most importantly, particle grading has emerged as a key material parameter, whose impact on earth building has often been overlooked. Particle grading appears to influence strength and stiffness even more than compaction effort, dry density and average particle size, which are usually quoted as the most important variables for the design of earth building materials.

Keywords: Suction; Hypercompaction; Strength; Particle size distribution; Earth construction

1. INTRODUCTION

The expression "raw earth" or "unstabilised earth" indicates a building material consisting of a compacted mix of soil and water, which is put in place with the least possible transformation [1]. Compared to standard engineering materials, raw earth can lead to a reduction in both carbon emissions and energy consumption not only during construction but also during service life of buildings [2,3]. The hydrophilic nature of raw earth explains the ability of this material to regulate humidity and temperature inside dwellings, thus increasing the comfort of occupants without requiring energy-intensive air conditioning installations [4]. Unfortunately, despite these advantages, the deployment of raw earth into construction practice has so far been very limited due to insufficient knowledge of important aspects of material design. For example, there is still considerable lack of information about the influence of index properties on the strength, stiffness and hygro-thermal inertia of earth materials at different humidity levels.

The engineering behaviour of earth building materials is strongly influenced by pore water content, which is in turn linked to the relative humidity of the surrounding air. A decrease of ambient humidity produces an increase of capillary suction with a corresponding decrease of pore water saturation, and vice versa. Climatic conditions change significantly with geographical location and seasonal variations of ambient conditions can be significant, yet relatively few studies have investigated the impact of relative humidity on the strength and stiffness of earth building materials [1,5-10]. These studies have indicated that both strength and stiffness increase non-linearly as suction increases and degree of saturation reduces, levelling off at very high suctions. This behaviour is consistent with the simple capillarity model of Fisher [11], which predicts that the stabilising effect of a water meniscus at the contact between soil particles grows with increasing suction tending towards an asymptote. An increase of humidity also leads to more ductile behaviour while a decrease of humidity generates a relatively brittle response, especially at high clay contents.

Jaquin et al. [1] were among the first to investigate the interaction between earth building materials and the surrounding atmosphere. They performed unconfined compression tests on air-dried samples at different water contents showing that strength and stiffness increase as water content decreases from 10.2 % to 5.5 %. This range of water content is, however, still higher than the typical value of 1-2 % measured inside earth building materials in field conditions [12]. Bui et al. [6] measured the unconfined compressive strength of earth materials with distinct particle gradings over a water content range from 11% to 1-2 %. These two limits correspond to the typical water contents of earth materials after manufacture and after field equalisation, respectively. Also in this case, the mechanical properties of the material deteriorated as water content increased and suction reduced. The study also highlighted that a small increase of moisture content from a typical field level of 1-2 % to about 4% (caused, for example, by intense rainfall or a marked change of ambient humidity) did not induce a significant drop of strength.

The impact of particle grading and clay content on material performance has been mostly overlooked by past research. Current earth building guidelines recommend specific classes of soils, whose particle size distribution and clay content must fit within admissible bands, but the effect of grading and clay content on the strength and durability of the material remains unclear [13]. Earlier studies [13-16] have suggested that soils with clay contents from as low as 5% to as high as 30% are acceptable for earth building, though there is still no consensus on clear selection criteria.

Beckett and Augarde [5] were among the few authors who investigated the effect of clay content on the strength of earth building materials showing that, regardless of humidity and temperature, a clay content near the recommended minimum corresponds to the highest material strength. They argued that this was due to the larger water retention capacity of clays, whose small pore network can hold moisture in bulk, rather than pendular, form over a very wide suction range [17]. This is also consistent with a large base of geotechnical research, which has demonstrated that finer soils exhibit higher water contents than coarser soils at any suction level [18]. A relatively high clay content therefore increases the moisture content of the earth material, which undermines strength and stiffness especially in humid environments. In another study, Xu et al. [10] amended a natural soil with different proportions of fine sand to produce three different earth building materials with clay contents of 35%, 26%, and 17%, respectively. They performed a series of triaxial tests on all three materials equalised at different humidity levels observing a strong dependency of the mechanical properties on both ambient humidity and clay content. Strength and stiffness decreased with an increase in relative humidity but the magnitude of this reduction depended on clay content. In contradiction with Beckett and Augarde [5], they observed that shear strength tended to increase with growing clay content under fixed levels of relative humidity and confining pressure. The magnitude of this increase tended to be smaller when humidity was larger due to the softening action of water. Other studies by Delinière et al. [19], Kouakou and Morel [20] and Taylor et al. [21] have also provided experimental evidence in agreement with the conclusions of Xu et al. [10]. Finally, Hamard et al. [22] reported that an increase in clay content does not always result in an increase of shear strength and that there is an optimum amount of clay that corresponds to a maximum value of shear strength. Beyond this optimum, a further increase of clay content leads to large material shrinkage and a reduction of shear strength. It must, however, be noted that the study by Hamard et al. [22] focused on ready-mixed clay plasters rather than compacted earth.

Past studies have also shown that denser earth exhibits larger values of stiffness and strength [9,23-26]. Bruno et al. [27] found that dry density increases less than linearly with growing compaction effort whereas strength and stiffness increase more than linearly with growing dry density. The strength of highly compacted earth is generally in the range 4.2-10 MPa [27], which is comparable to the strength of chemically stabilised earth materials [28-31]. Particle grading may therefore play an important role in the design of earth building materials as it governs the ability of the soil grains to assemble into a denser structure when compacted under a given effort.

This paper explores the above issues by presenting an experimental investigation of the simultaneous effects of particle grading, dry density and ambient humidity on the mechanical behaviour of unstabilised earth building materials. Unlike previous laboratory studies, which have been mostly restricted to unconfined compression tests, this paper focuses on the measurement of stiffness and strength inside a triaxial cell under variable levels of radial confinement.

2. MATERIALS AND METHODS

2.1. EARTH CHARACTERISATION

The base soil used in the present work has been provided by the brickwork factory Bouisset from the region of Toulouse (France). Figure 1 shows the particle size distribution of this base soil [32] together with the recommended lower and upper limits according to current guidelines for the manufacture of compressed earth bricks [33-35].

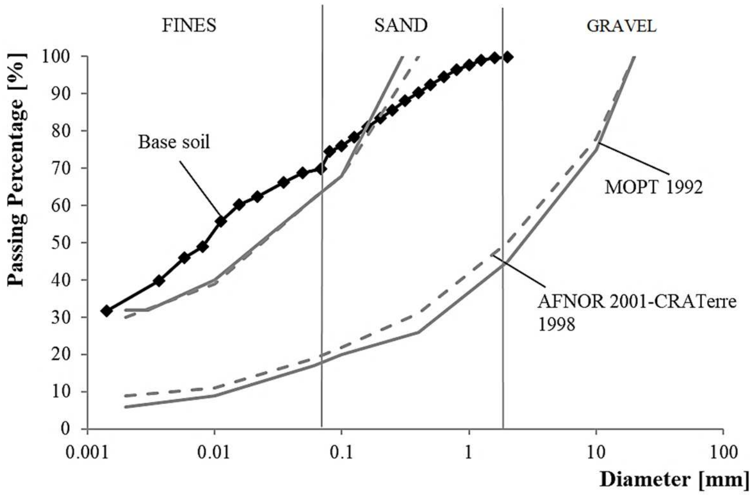


Figure 1: Particle size distribution of the base soil in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and MOPT [35] (after Cuccurullo et al. [32]).

The main properties of the base soil, including the Atterberg limits of the fine fraction (i.e. the fraction smaller than 0.400 mm), were determined in a previous publication [32] and are summarised in Table 1. Past studies [36] have also indicated a predominantly kaolinitic clay fraction with a limited tendency to swell/shrink upon wetting/drying, which is advantageous for earth building. Figure 2 shows the plasticity properties of the soil with reference to the Casagrande chart, which classifies this material as a low plasticity clay [32]. Figure 2 also indicates that the soil fits inside the recommended plasticity region for the manufacture of compressed earth bricks according to AFNOR [33]; CRATerre–EAG [34] and Houben and Guillaud [37].

Table 1: Main properties of the base soil (from Cuccurullo et al. [32]).

Particle size distribution		**Atterberg limits**	
Gravel content (> 2 mm, %)	0	Plastic limit w_P (%)	18.7
Sand content (≤ 2 mm, %)	31	Liquid limit w_L (%)	29.0
Silt content (≤ 63 µm, %)	35	Plasticity index I_P (%)	10.3
Clay content (≤ 2 µm, %)	34	**Mineralogical composition**	
Clay activity A (-)	0.30	Goethite, Muscovite, Orthose, Kaolinite, Quartz, Calcite	
Specific gravity G_s (-)	2.65		

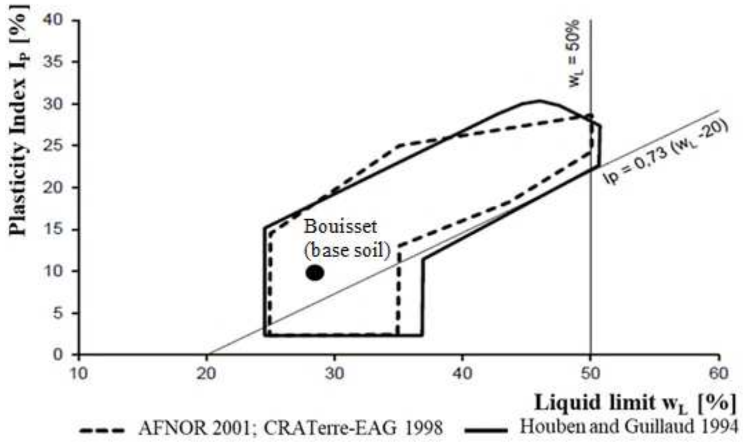


Figure 2: Plasticity properties of the base soil in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and Houben and Guillaud [37] (from Cuccurullo et al. [38]).

The base soil was then blended with 68% of silica sand (by overall dry mass) to obtain a second earth mix with a clay content equal to the recommended minimum [32]. Figure 3 shows the particle size distribution of the added sand, whose grading is monodispersed with particle dimensions between 0.06 and 2 mm.

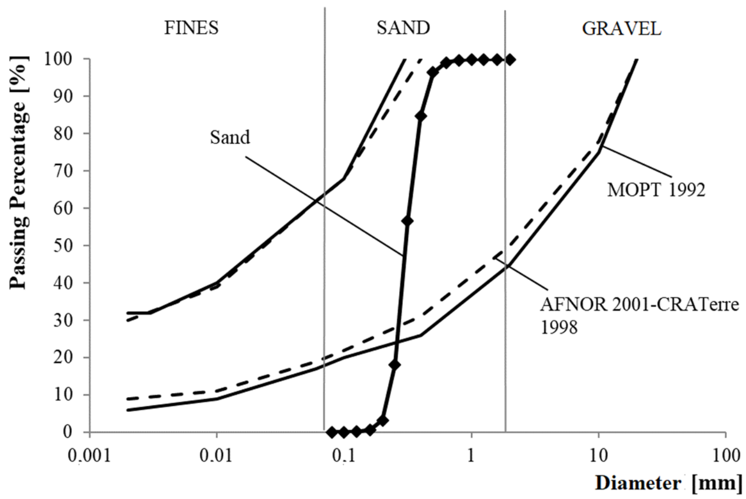


Figure 3: Particle size distribution of added sand in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and MOPT [35] (after Cuccurullo et al. [32]).

Table 2 summarizes the composition of the two earth building materials considered in this study, i.e. earth mix 1, which is the base soil, and earth mix 2, which is the blend of base soil and silica sand. Figure 4 shows the particle size distributions of these two mixes in relation to the recommended limits for the manufacture of compressed earth bricks [33-35]. Inspection of Figure 4 indicates that earth mix 1 exhibits a well-graded particle distribution, which is slightly finer than the upper limit and a clay content coinciding with the maximum recommended value. Conversely, earth mix 2 exhibits a poorly-graded particle size distribution, which cuts through the admissible band with a clay content corresponding to the minimum recommended value. The particle size distribution of earth mix 2 falls entirely inside the recommended grading band while that of earth mix 1 is slightly outside. The deviation of earth mix 1 from current guidelines is, however, not significant and both mixes are assumed to be compliant with existing recommendations.

Table 2: Composition of the two earth materials tested in the present work (after Cuccurullo et al. [32]).

Material	Base soil percentage [%]	Added sand percentage [%]	Clay content [%]
Earth mix 1 (base soil)	100	0	≈32
Earth mix 2	32	68	≈10

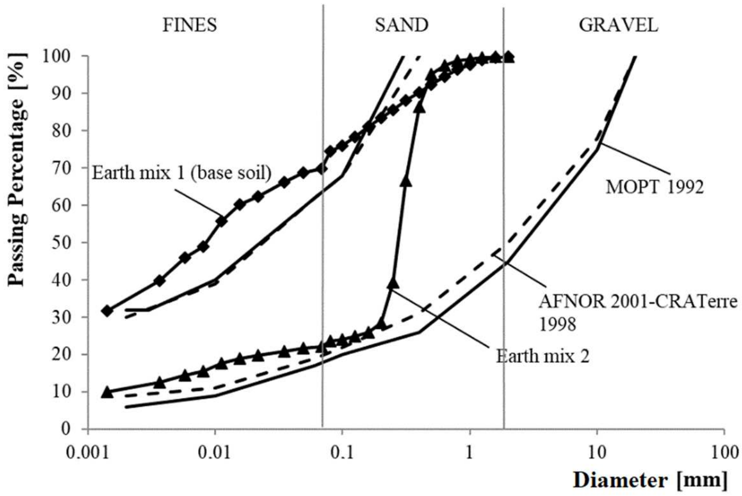


Figure 4: Particle size distribution of earth mixes in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and MOPT [35] (after Cuccurullo et al. [32]).

2.2 EARTH COMPACTION

Figure 5 presents the standard Proctor compaction curve of earth mix 1, which was determined by Cuccurullo et al. [38] in compliance with the French norm NF P94-093 [39]. For ease of interpretation, Figure 5 also shows the equisaturation lines, which converge towards the ‘‘no porosity’’ point corresponding to a water content of zero and a dry density equal to that of the soil particles. Inspection of Figure 5 indicates a maximum dry density of 1.97 g/cm^3, which corresponds to an optimum water content of 12.4%.

Figure 6 shows instead the hypercompaction curves for earth mixes 1 and 2, which were obtained by applying a large static vertical pressure of 100 MPa [32] to the sample inside a 50 mm diameter cylindrical mould using a load-controlled Zwick/Roell Amsler HB250 press with a capacity of 250 kN. The earth was compacted by two cylindrical pistons acting at the top and bottom as this increased the uniformity of compaction stress, and hence material fabric, across the sample height compared to the case of single compression where the load is applied on only one side. This is because, during double compression, the friction between the earth and the mould creates two opposite gradients of the compaction stress extending from each sample extremity to the middle section. Conversely, during single compression, the friction generates only one gradient of compaction stress extending between the two extremities of the sample. Additional details of the hypercompaction procedure are available in Cuccurullo et al. [32] and Bruno [27].

Inspection of Figure 6 shows that the finer and well graded earth mix 1 exhibits considerably higher values of dry density compared to the coarser and poorly graded earth mix 2. The optimum water content is 4.88 % for earth mix 1 and 6.50 % for earth mix 2, while the maximum dry densities are 2.31 g/cm^3 and 2.12 g/cm^3, respectively. Comparison of Figures 5 and 6 also indicates that the hypercompaction procedure results in a significantly denser material with a considerably lower value of the optimum water content compared to standard Proctor compaction.

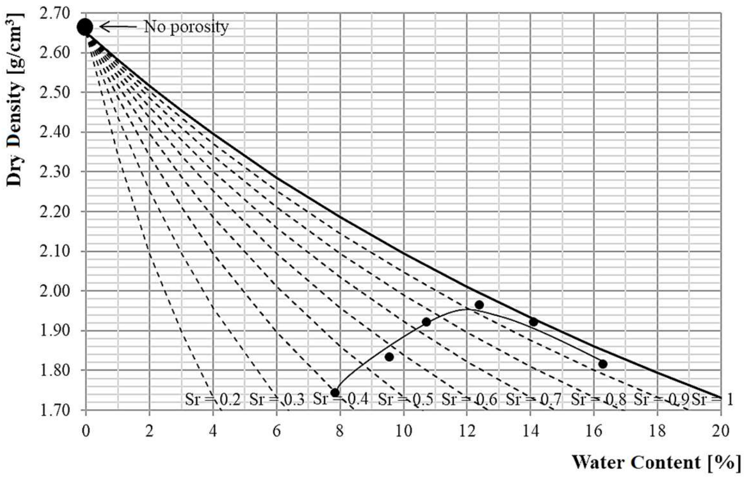


Figure 5: Standard Proctor compaction curve for earth mix 1 (after Cuccurullo et al. [38]).

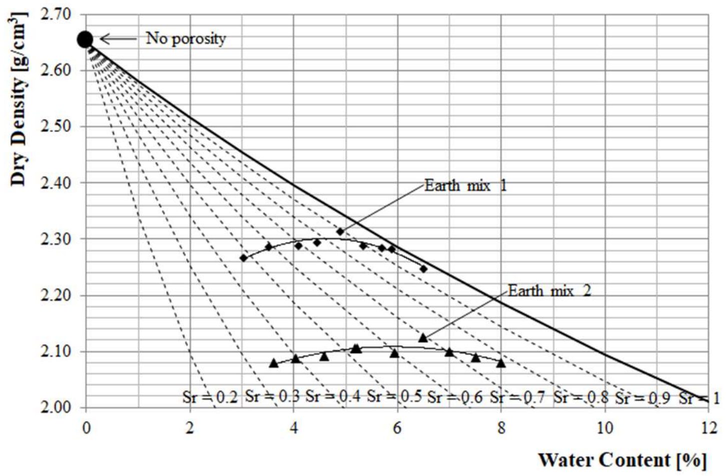


Figure 6: Hypercompaction curves, corresponding to the application of a static pressure of 100 MPa, for earth mixes 1 and 2 (after Cuccurullo et al. [32]).

2.3 TRIAXIAL TESTING PROGRAM

Triaxial samples of 50 mm diameter and 100 mm height were manufactured by one-dimensional static compaction under either an equivalent Proctor load (Proctor compacted samples) or a pressure of 100 MPa (hypercompacted samples).

Proctor compacted samples of earth mix 1 were fabricated by sieving the dry material through a 2 mm mesh and subsequently mixing it with the optimum water content of 12.4 % (see Figure 5). The moist soil was then statically compacted in 10 layers to attain the maximum Proctor dry density (see Figure 5), taking care to scarify the surface of each layer before adding the next one. The hypercompacted samples of earth mixes 1 and 2 were instead fabricated at their respective optimum water contents, i.e. 4.88 % and 6.50 % (see Figure 6), following the procedure described in the previous section.

Twelve samples of each of the three materials (i.e. Proctor compacted earth mix 1, hypercompacted earth mix 1 and hypercompacted earth mix 2) were manufactured and divided into four sets of three samples. One set was oven-dried for three days at a temperature of 105 °C while the other three sets were equalised inside a climatic chamber at humidity levels of 25%, 62% and 95%, respectively, and constant temperature of 25 °C. The samples in the climatic chamber were weighed every day until equalisation, which was assumed to be complete when the sample mass changed less than 0.1 % over at least one week (this took generally 15 days). After equalisation, the average mass W and volume V of each set of three samples was measured. The total suction, ψ was also determined from the imposed values of temperature, T and relative humidity, RH according to Kelvin's law as:

$$\psi = -\frac{R\,T}{V_m}\ln(RH) \qquad (1)$$

where R is the gas constant and V_m is the molar volume of water.

At the end of each triaxial test, three earth fragments of about 50 grams were taken at the top, middle and bottom of the sample to determine the corresponding water contents according to the French norm NF P 94-050 [40]. The average water content w was then calculated from these three measurements for each of the three samples equalised at the same humidity level. All measurements were generally very similar, thus confirming the uniformity of moisture content across the samples. By assuming no variation of moisture content during the triaxial tests, the average values of bulk density ρ_b, dry density ρ_d, void ratio e, degree of saturation S_r and porosity n at the start of the tests were calculated from the volume V, mass W and water content w (taking a specific gravity G_s equal to the value reported in Table 1) as:

$$\rho_b = \frac{W}{V} \qquad (2)$$

$$\rho_d = \frac{\rho_b}{(1+w)} \qquad (3)$$

$$n = 1 - \frac{\rho_d}{\rho_w\,G_s} \qquad (4)$$

$$S_r = \frac{w\;\rho_d}{n\;\rho_w} \qquad (5)$$

Table 3 summarises the average properties at the start of the triaxial tests for each set of three samples equalised at the same humidity level or oven-dried. Recall that pore moisture is assumed to remain unchanged during the triaxial tests and, therefore, the values of water content in Table 3 are the same at the start and the end of the triaxial tests. Due to experimental problems, reliable measurements of water content could not be obtained for the hypercompacted samples of earth mix 2 equalised at the humidity levels of 62% and 95%, which explains the gaps in Table 3. The value of total suction of the oven-dry material is also absent from Table 3 as it could not be calculated from Equation 1 due to absence of information about the ambient humidity inside the furnace.

Table 3: Average samples properties at the start of the triaxial test, i.e. after equalisation at different humidity levels or oven-drying.

Relative humidity, *RH* [%]	Bulk density, ρ_b [g/cm^3]	Water content, *w* [%]	Dry density, ρ_d [g/cm^3]	Porosity, *n* [%]	Degree of saturation, S_r [%]	Total suction, ψ [MPa]
Hypercompacted earth mix 1						
Oven-dry	2.28	0	2.28	14.1	0	-
RH = 25 %	2.31	0.68	2.29	13.4	11.7	190
RH = 62 %	2.33	2.24	2.28	13.9	36.7	65
RH = 95 %	2.38	4.61	2.28	14.0	74.9	7
Hypercompacted earth mix 2						
Oven-dry	2.12	0	2.12	20.1	0	-
RH = 25 %	2.12	0.36	2.11	20.3	3.78	190
RH = 62 %	2.15	-	-	-	-	65
RH = 95 %	2.13	-	-	-	-	7
Proctor compacted earth mix 1						
Oven-dry	1.95	0	1.95	26.3	0	-
RH = 25 %	1.99	0.88	1.97	25.6	6.76	190
RH = 62 %	1.98	2.43	1.93	27.1	17.3	65
RH = 95 %	2.09	4.91	1.99	24.9	39.3	7

Inspection of Table 3 indicates that the equalisation of earth mix 1 at distinct humidity levels produces distinct degrees of saturation and that the difference between degrees of saturation is more marked for the hypercompacted samples than for Proctor compacted ones. This also suggests that the sensitivity of degree of saturation to ambient humidity is higher for earth building materials than standard geotechnical fills due to the higher density of the former materials compared to the latter ones. Note also that these differences of degree of saturation correspond to distinct magnitudes of inter-particle capillary bonding and, therefore, distinct levels of strength and stiffness as discussed later in the paper.

The equalised or oven-dried samples were sheared inside a triaxial cell with an axial displacement rate of 0.06 mm/min. Throughout the triaxial tests, the back-pressure line was open to the atmosphere to allow the drainage of pore air from the unsaturated samples. The flow of vapour through the back-pressure line was, however, considered negligible and the sample water content was therefore assumed constant. Shearing was continued until failure, which generally took between 23 and 35 minutes depending on the test. For each humidity level, three samples were sheared under different radial stresses of 0 kPa, 300 kPa and 600 kPa, respectively, to explore the effect of earth confinement inside thick walls.

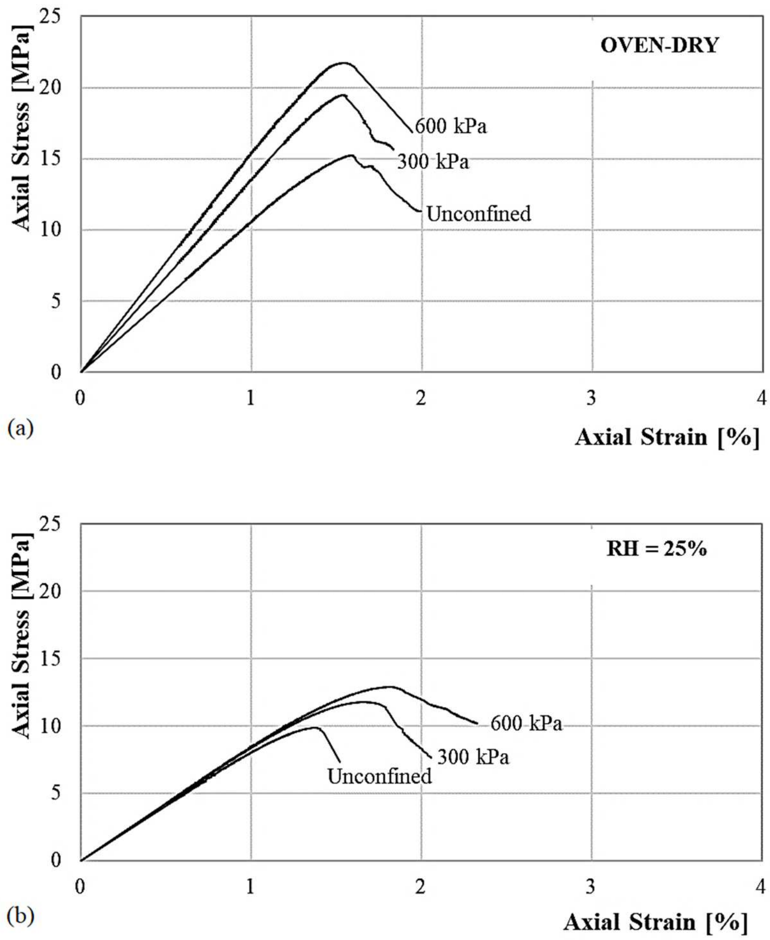
Test results were subsequently processed to determine the initial Young's modulus and the peak strength for each confining pressure and humidity level. In particular, the initial Young's modulus was measured as the slope of the stress-strain curve over the low-pressure range, i.e. up to 20% of the peak strength, where the material response is reasonably linear.

3 RESULTS AND DISCUSSION

Figure 7 shows the stress-strain curves measured during the triaxial tests of the hypercompacted samples of earth mix 1 equalised at distinct humidity levels. For each humidity level, three curves are reported corresponding to distinct degrees of lateral confinement. Inspection of Figure 7 indicates that, at a given humidity level, the peak strength increases by a margin of between 30% and 50% as the radial stress increases from zero to 600 kPa, which highlights the beneficial effect of lateral confinement on material strength.

Moreover, at a given confining pressure, the peak stress increases as the ambient humidity decreases, which provides further evidence of the inverse relationship between strength and degree of saturation due to the progressive formation of capillary menisci at particle contacts during desaturation. These capillary water menisci bond earth grains together and therefore enhance the strength of the material [5,41]. The largest levels of strength, from 15 MPa to more than 20 MPa, were measured on dry samples which should by definition contain no capillary water at all. These samples should, therefore, be no different from water saturated ones and should thus exhibit the lowest values of strength instead of the highest ones. This apparent contradiction is due to the conventional assumption of oven-dryness as the reference material state corresponding to complete absence of pore water. In reality, even inside oven-dry samples there is a residual presence of adsorbed water subjected to extremely high tensile stresses, which firmly bonds earth particles together.

Inspection of Figure 7 also indicates that the material response changes from fragile to ductile as humidity increases, with the highest level of brittleness observed on the oven-dry samples. Therefore, an increase of ambient humidity produces a reduction of shear strength while enhancing the ability of the material to undergo plastic deformation before failure.



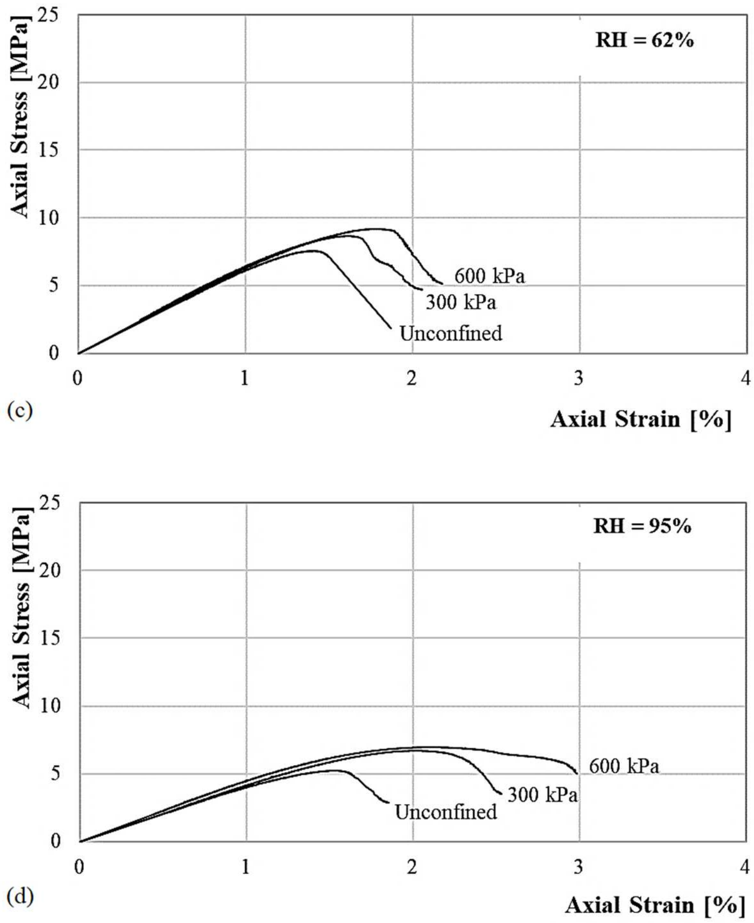
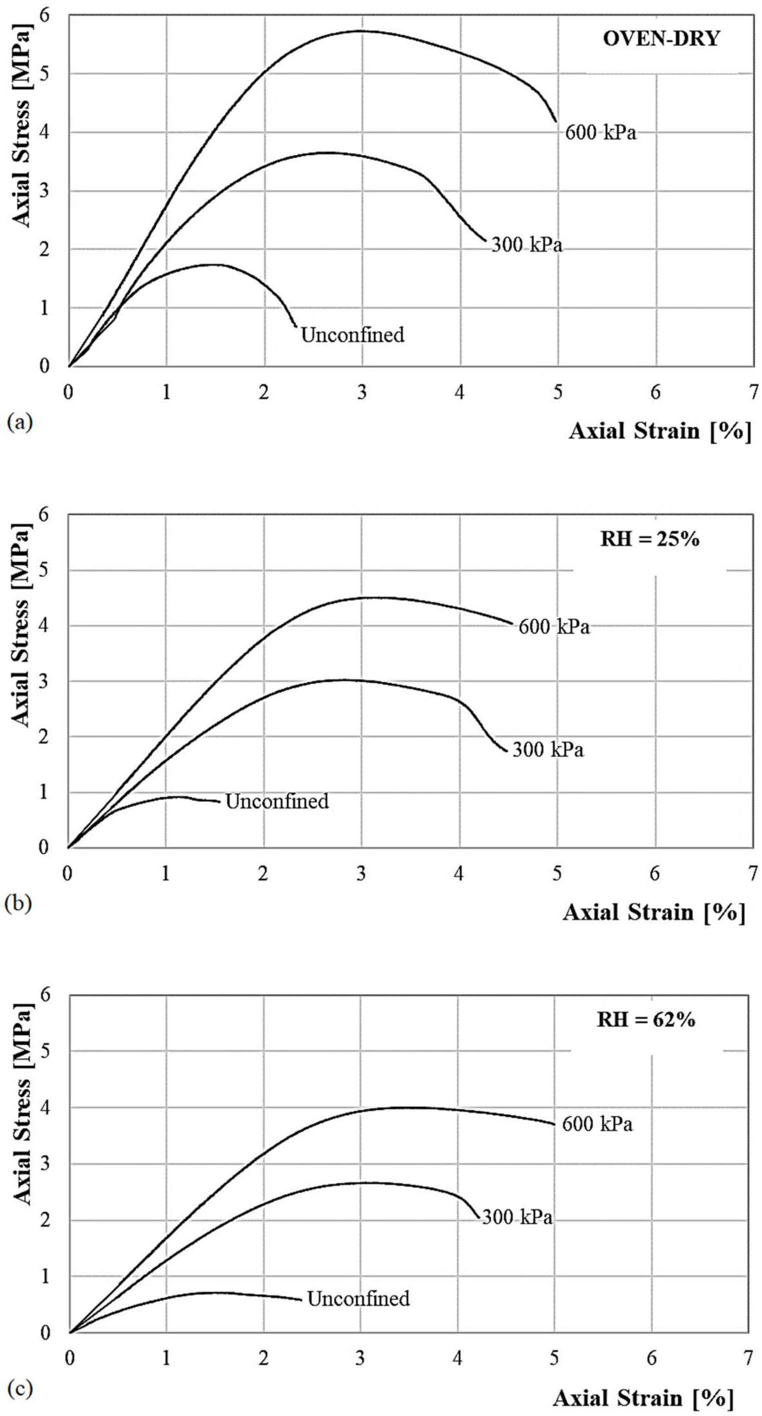


Figure 7: Results from triaxial tests on the hypercompacted earth mix 1 at different confining pressures and distinct humidity levels: oven-dry (a), 25 % (b), 62 % (c), 95 % (d).

Figure 8 presents the stress-strain curves measured during the triaxial tests of the hypercompacted samples of earth mix 2 showing, once again, that peak strength increases as relative humidity decreases at all confining pressures. As in the case of earth mix 1 (Figure 7), the highest strength levels were measured on the oven-dry samples with a maximum of about 6 MPa, which is, however, significantly lower than the corresponding strength of earth mix 1. Inspection of Figure 8 also confirms that, as relative humidity grows, the behaviour changes from fragile to ductile, thus increasing the ability of the material to deform plastically before failure. The beneficial effect of lateral confinement is more marked than in the previous case, with an up to six-fold increase of strength as the radial stress grows from zero to 600 kPa at constant humidity.

The comparison of the triaxial responses of earth mix 2 (Figure 8) and earth mix 1 (Figure 7) indicates that strength and brittleness are significantly lower in the former case compared to the latter one, despite the two mixes are both hypercompacted and exhibit particle size distributions that are both admissible according to existing guidelines (Figure 4). The main difference between these two mixes consists in the dispersion of grain sizes, which corresponds to a well-graded fine material in the case of earth mix 1 and a poorly-graded coarse material in the case of earth mix 2. This diversity of grading is also reflected in the significantly different levels of dry density for the same compaction effort and water content (Figure 6). Distinct materials inside the admissible grading band of Figure 4 can therefore generate very different mechanical responses even when compacted under similar conditions. In particular, the results from this study indicate that a fine well-graded earth generates higher strength levels than a coarse poorly-graded earth under similar compaction conditions. Thus, the role of particle grading may outstrip that of average particle size, which means that coarser materials will not always generate higher strength levels.



OVEN-DRY
Axial Stress [MPa]
Axial Strain [%]
600 kPa
300 kPa
Unconfined
(a)
RH = 25%
Axial Stress [MPa]
Axial Strain [%]
600 kPa
300 kPa
Unconfined
(b)
RH = 62%
Axial Stress [MPa]
Axial Strain [%]
600 kPa
300 kPa
Unconfined
(c)

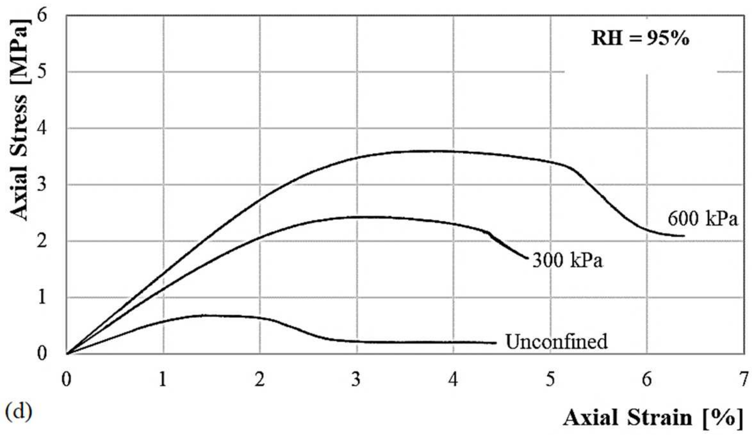
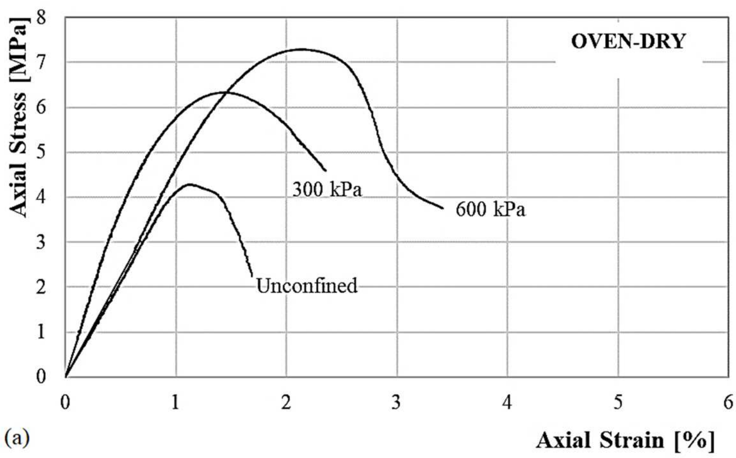
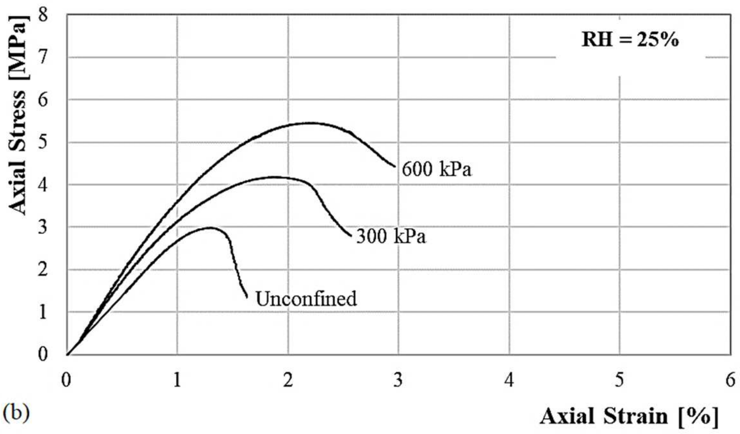


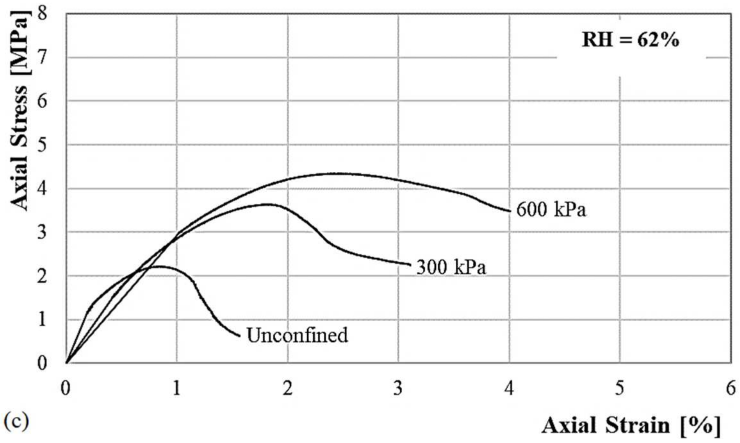
Figure 8: Results from triaxial tests on the hypercompacted earth mix 2 at different confining pressures and distinct humidity levels: dry (a), 25 % (b), 62 % (c), 95 % (d).

Figure 9 shows the stress-strain curves of the triaxial tests on the Proctor samples of earth mix 1 from which the same conclusions as before can be drawn regarding the qualitative effect of ambient humidity on material strength. Inspection of Figure 9 also indicates an up to three-fold increase of strength with growing radial stress from 0 to 600 kPa at constant humidity, which represents an intermediate response compared to the previous two materials. Most importantly, the strength levels measured on the Proctor compacted samples of earth mix 1 are generally higher than those recorded on the hypercompacted samples of earth mix 2 (Figure 8), despite the former samples exhibit a markedly lower density than the latter ones. An earth material of relatively low density with a well-graded particle size distribution can therefore exhibit higher strength levels that those of a considerably denser material with a poorly-graded distribution. This confirms the key role of particle grading in enhancing material strength, a role which is more significant than that of material density. This important conclusion has not found adequate space in previous studies, which have instead focused on compaction effort as the main means of improving material strength.

Finally, a comparison between test results on Proctor compacted (Figure 9) and hypercompacted (Figure 7) samples of earth mix 1 shows that strength levels are significantly higher in the latter case than in the former one. This is expected as, for a given particle size distribution, a stronger compaction effort generates a larger material density and, hence, higher strength levels. Proctor compacted samples show, however, greater ductility compared to hypercompacted ones, which is consistent with previous observations of increasing ductility with decreasing strength, especially at high humidity levels.







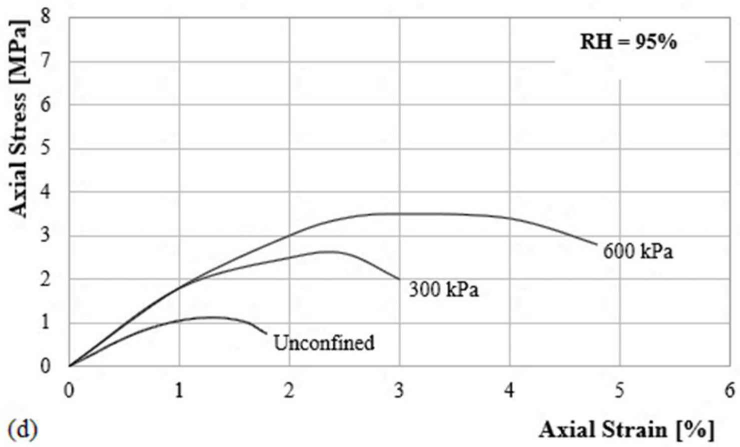


Figure 9: Results from triaxial tests on the Proctor compacted earth mix 1 at different confining pressures and distinct humidity levels: dry (a), 25 % (b), 62 % (c), 95 % (d).

Figure 10 summarizes the evolution of strength (i.e. the peak axial stress) with relative humidity for the three materials subjected to confining pressures of 0 kPa, 300 kPa and 600 kPa. For earth mix 1, hypercompaction increases the sensitivity of material strength to humidity variations compared to Proctor compaction. This result is consistent with previous data in Table 3 showing that hypercompacted samples, equalised at different humidity levels, exhibit greater differences of degree of saturation than Proctor compacted ones. As the degree of saturation is inversely related to the inter-particle capillary bonding, a larger variation of degree of saturation with changing humidity should correspond to a larger variation of strength.

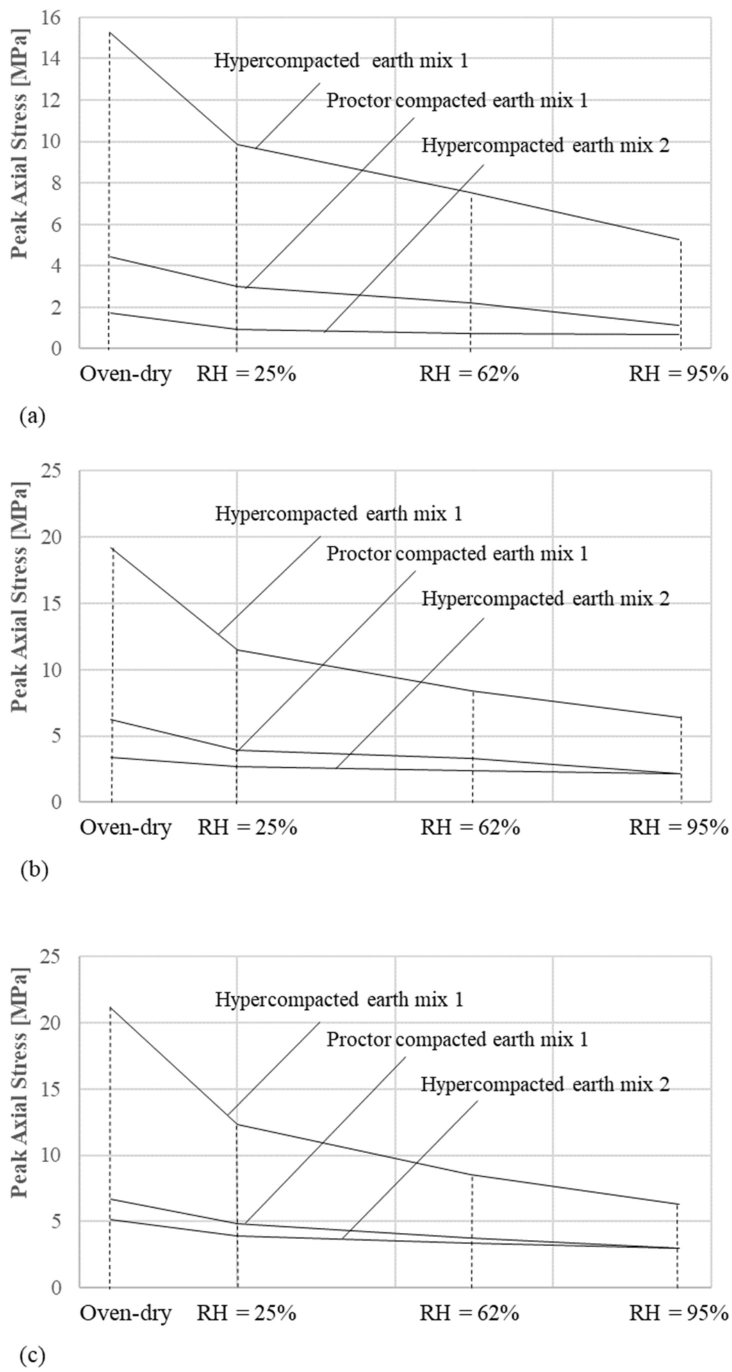


Figure 10: Evolution of strength (i.e. peak axial stress) with relative humidity at different confining pressures: unconfined (a), 300 kPa (b) and 600 kPa (c).

The effect of degree of saturation on the mechanical properties of each material can be synthetically described by comparing their strength and stiffness envelopes at distinct humidity levels.

The strength envelopes at constant humidity are obtained by plotting the values of peak deviator stress q measured from the three triaxial tests under different radial stresses against the corresponding values of mean stress p. These experimental data are then interpolated by the following linear equation:

$$q = C + M\,p \tag{7}$$

where the coefficients *C* and *M* are respectively the intercept and slope of the strength envelope at each humidity level. The above coefficients can also be converted into the corresponding values of cohesion *c* and friction angle *φ* by means of the following equations:

$$M = \frac{6\sin\varphi}{3-\sin\varphi} \tag{8}$$

$$C = \frac{6\,c\cos\varphi}{3-\sin\varphi} \tag{9}$$

Figures 11, 12 and 13 show the strength envelopes of the hypercompacted earth mix 1, hypercompacted earth mix 2 and Proctor compacted earth mix 1, respectively. Similarly, Tables 4, 5 and 6 summarise the strength parameters of the hypercompacted earth mix 1, hypercompacted earth mix 2 and Proctor compacted earth mix 1, respectively.

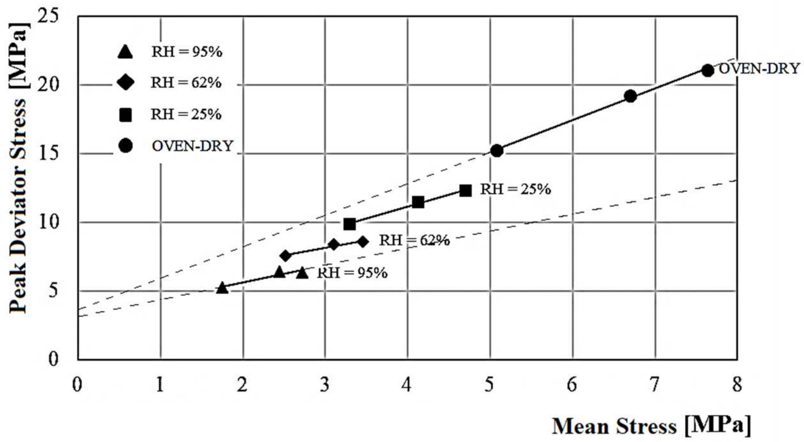


Figure 11: Strength envelopes of hypercompacted earth mix 1 at different humidity levels.

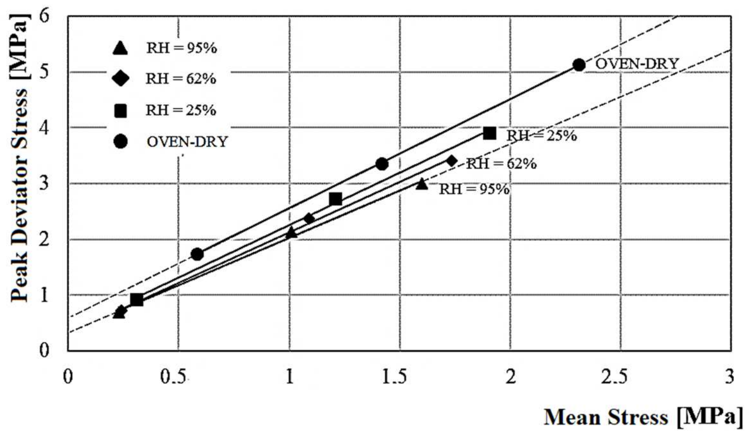


Figure 12: Strength envelopes of hypercompacted earth mix 2 at different humidity levels.

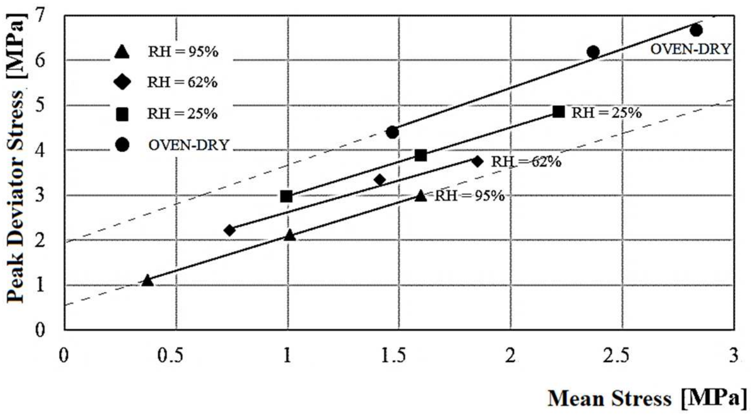


Figure 13: Strength envelopes of Proctor compacted earth mix 1 at different humidity levels.

Table 4: Strength parameters of hypercompacted earth mix 1 at different humidity levels.

	M **[-]**	***φ*** **[°]**	***C*** **[MPa]**	***c*** **[MPa]**
OVEN-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

Table 5: Strength parameters of hypercompacted earth mix 2 at different humidity levels.

	M **[-]**	***φ*** **[°]**	***C*** **[MPa]**	***c*** **[MPa]**
OVEN-DRY	1.96	47.4	0.60	0.33
RH = 25 %	1.88	45.7	0.38	0.21
RH = 62 %	1.80	43.9	0.32	0.18
RH = 95 %	1.70	41.4	0.34	0.17

Table 6: Strength parameters of Proctor compacted earth mix 1 at different humidity levels.

	M **[-]**	***φ*** **[°]**	***C*** **[MPa]**	***c*** **[MPa]**
OVEN-DRY	1.72	41.9	1.94	1.01
RH = 25 %	1.53	37.5	1.46	0.73
RH = 62 %	1.41	34.9	1.22	0.60
RH = 95 %	1.53	37.6	0.56	0.29

Inspection of Figures 11-13 and Tables 4-6 indicates that an increase of ambient humidity produces a decrease of friction angle that is more marked in the hypercompacted samples than in the Proctor compacted ones. Among the hypercompacted samples, the decrease is most evident for earth mix 1 as, in this case, the value of the friction angle decreases from 56.6° to 30.8° as the humidity level increases from oven-dry conditions to 95% (Table 4). As for the Proctor compacted samples of earth mix 1, the friction angle changes relatively little with ambient humidity as shown by the approximately parallel strength envelopes of Figure 13.

Conversely, a variation of ambient humidity produces a change of cohesion that, in relative terms, is more modest for the hypercompacted samples (Tables 4 and 5) than for the Proctor compacted ones (Table 6). This is graphically shown in Figures 11 and 12 where the strength envelopes of the hypercompacted materials tend to converge towards a narrow area as the mean stress reduces towards zero. The trend is clearest for the hypercompacted earth mix 1, whose cohesion is approximately constant at all humidity levels (Table 4) - except for a deviation at a humidity of 95 % when a larger scatter of data is also observed.

Figures 14, 15 and 16 show the stiffness envelopes of the hypercompacted earth mix 1, hypercompacted earth mix 2 and Proctor compacted earth mix 1, respectively. These envelopes are obtained by plotting the values of the initial Young's modulus E, measured from the three triaxial tests under different confinement levels, against the corresponding values of radial stress σ at each humidity level. Inspection of Figures 14, 15 and 16 indicates that, as already observed for the strength, an increase of ambient humidity produces a decrease of stiffness. The effect of confinement on stiffness is less evident compared to strength as the Young's modulus remains relatively constant with growing radial stress at constant humidity. Only in the case of the oven-dry samples there is a clear increase of stiffness with growing radial confinement. In general, stiffness measurements present a larger scatter and a more uncertain trend compared to strength measurements, which reflects the relatively high inaccuracies associated to the determination of the initial Young's modulus.

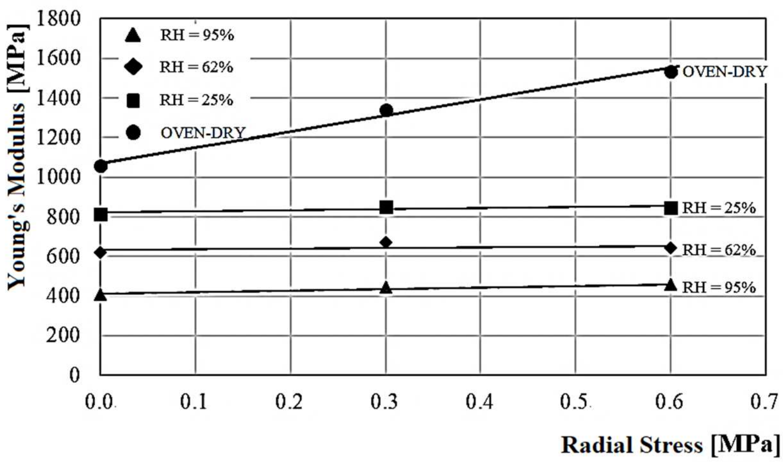


Figure 14: Stiffness envelopes of hypercompacted earth mix 1 at different humidity levels.

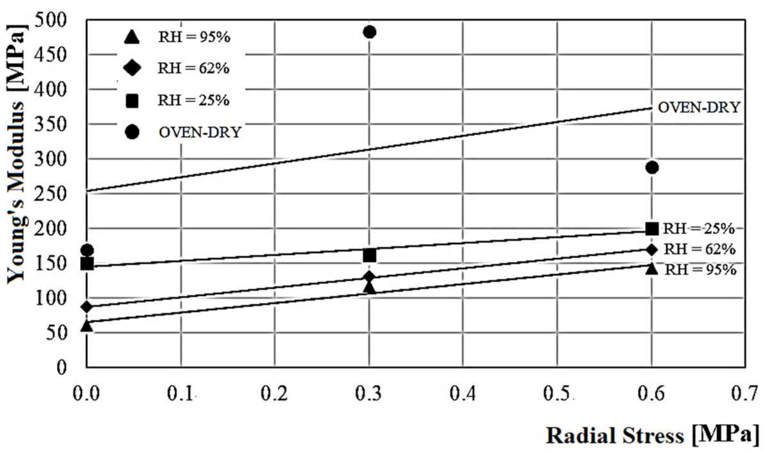


Figure 15: Stiffness envelopes of hypercompacted earth mix 2 at different humidity levels.

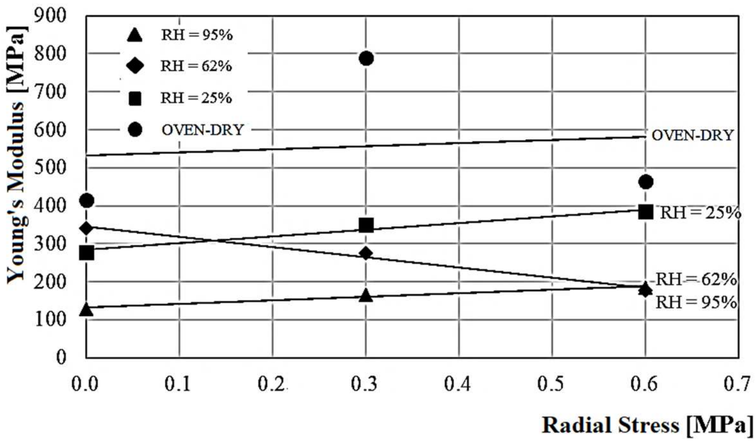


Figure 16: Stiffness envelopes of Proctor compacted earth mix 1 at different humidity levels.

4 CONCLUSIONS

The mechanical properties of compacted soils strongly depend on dry density and this emphasizes the specific nature of earth building materials, which are generally much denser than standard geotechnical fills. This paper has presented an experimental investigation of the simultaneous effects of dry density, ambient humidity and particle grading on the mechanical behaviour of three earth building materials manufactured from soils with markedly distinct particle size distributions and compacted under significantly different efforts.

From this investigation, particle grading has emerged as a key parameter, whose influence on the mechanical performance of earth building materials has often been overlooked but it appears even more important than that of dry density or average particle size. This study has, for example, shown that the strength and stiffness of a Proctor compacted well-graded fine earth can be considerably higher than those of a hypercompacted poorly-graded coarse earth, despite the density of the former material is much lower than that of the latter one. This result is even more surprising if one considers that both those earths exhibit index properties (i.e. particle size distribution and plasticity characteristics) that comply with current earth building recommendations. The observed differences of strength and stiffness must therefore be entirely ascribed to disparities of particle grading. This finding should prompt further research on the optimisation of earth mixes for building applications together with a revision of current guidelines for the selection of suitable materials.

In line with previous investigations, the present study has also found that: a) material ductility grows with decreasing strength and increasing ambient humidity, b) mechanical characteristics tend to improve with growing dry density and c) growing levels of ambient humidity produce an increase of degree of saturation with a consequent deterioration of strength and stiffness.

Finally, shear strength increases significantly as the confining stress grows at all humidity levels, which highlights the beneficial effect of the lateral confinement inside thick walls. Conversely, material stiffness remains generally constant as lateral confinement increases at any level of ambient humidity. The magnitude of the increase of shear strength with lateral confinement depends on both particle grading and material density. In this work, it has been found that the beneficial effect of lateral confinement becomes more evident as dry density decrease and particle grading becomes poorer.

5 ACKNOWLEDGEMENTS

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