A comparative study of the effects of particle grading and compaction effort on the strength and stiffness of earth building materials at different humidity levels

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ABSTRACT: This paper presents an investigation of the mechanical properties of three different earth building materials that have been manufactured by compacting two soils with markedly distinct particle size distributions under two substantially different efforts. Distinct samples of each one of the three materials have been equalised inside a climatic chamber at different humidity levels or have been oven-dried, before being subjected to shearing inside a triaxial cell to measure the corresponding levels of strength and stiffness. Triaxial shearing has also been performed under different levels of radial stress to investigate the influence of the lateral confinement of the material inside building 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 both these properties strongly depends on the material dry density and clay content. Most importantly, particle grading has emerged as a key material parameter, whose impact on earth building has often been overlooked in the past. Particle grading now appears to influence strength and stiffness even more than compaction effort, dry density and average particle size, which are typically quoted as some of the most important variables in the design of earth building materials.

Keywords: Suction; Hyper-compaction; 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, water and sometimes stabilising additives, which is put in place with the least possible transformation [1]. Compared to standard engineering materials, the use of raw earth can lead to reductions in both carbon emissions and energy consumption not only during the construction but also during the service life of a building [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 [4]. Unfortunately, despite these advantages, the deployment of raw earth into construction practice has so far been very limited due to the insufficient knowledge of important aspects of material design. For example, there is still considerable lack of information about the influence of the index properties of the earth (e.g. particle grading) on the strength, stiffness and hygro-thermal inertia of the compacted material at different ambient 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. Experimental procedure replicating climatic conditions in different regions of the world are, however, still scarce and only few studies have focused on the impact of relative humidity on pore suction and material strength [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 levels of suction. These findings are also consistent with the Fisher [11] capillarity model, which predicts that the stabilising effect of a water meniscus at the contact between two spherical particles grows with increasing suction towards an asymptote.

Jaquin et al. [1] were among the first to investigate the interaction between earth building materials and surrounding atmosphere by performing unconfined compression tests on samples air-dried to different water contents. The study showed that strength and stiffness increase when water content decreases from 10.2 % to 5.5 %, which is however still higher than the typical water content of 1-2 % in field conditions [12]. Similarly, Bui et al. [6] measured the unconfined compressive strength of earth materials with different grading over a range of water contents from a level of about 11%, corresponding to the condition immediately after manufacture, to 1-2 %, corresponding to the condition after equalisation in the field. Also in this case, the mechanical properties of the material exhibited a progressive deterioration with increasing water content increased and reducing suction. Nevertheless, the study highlighted that a slight increase of pore moisture from the field level of 1-2 % to no more than 4% (due, for example, to intense rainfall or a change of ambient humidity) did not induce a significant drop of strength.

Interestingly, the impact of particle grading and clay content on material performance has been mostly overlooked by past research. Current earth building guidelines only recommend specific classes of soils, whose particle size distribution and clay content fit within admissible bands, but the effect of grading and clay content on strength and durability remains unclear [13]. Earlier studies [13-16] have suggested that soil with clay content varying from as low as 5% to as high as 30% is acceptable for earth buildings. However, despite all the given recommendations, there is still no consensus on a generalized set of selection criteria for soil used for earthen construction.

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 levels, a clay content near the recommended minimum corresponds to the highest material strength. They argued that this behaviour is due to the larger water retention of the clay fraction as, at any given suction, the smaller pore network of finer soils holds moisture in bulk rather than pendular form [17]. A large base of geotechnical research has also demonstrated that finer soils exhibit higher water contents than coarser soils at any given suction level [18]. A relatively high clay content might therefore undermine the strength of earth building materials, 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 then performed a series of triaxial tests on all three materials equalised at different levels of relative humidity observing that the mechanical properties strongly depend on both ambient humidity and clay content. In particular, both shear strength and stiffness decreased with an increase in relative humidity but the magnitude of the reduction depended on the clay content. An increase in relative humidity led to more ductile behaviour while a lower relative humidity produced a relatively brittle response, especially at high clay contents. In contradiction with Beckett and Augarde [5], they observed that, for the same levels of relative humidity and confining pressure, the shear strength tended to increase with growing clay content (within the range of values investigated). However, the magnitude of this increase tended to decrease with increasing relative humidity due to the softening action of water on clay. Other studies e.g. Delinière et al. [19], Kouakou and Morel [20] and Taylor et al. [21] have also verified the above conclusions. Conflicting opinions have been raised instead by Hamard et al. [22], who reported that an increase in clay content does not always result in an increase in shear strength and that there is an optimum clay content corresponding to the maximum shear strength. Beyond this optimum value, a further increase of clay content leads to more shrinkage, and thereby to a reduction in shear strength, although it should be noted that these studies [22] specifically focused on ready-mixed clay plasters rather than compacted earth.

Past studies have also shown that denser earth materials exhibit 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 between 4.2-10MPa [27], which is comparable to the strength of chemically stabilised earth materials [28-31]. In this respect, particle grading may play an important role as it governs the ability of the earth to assemble into a dense structure when compacted under a given effort.

This paper addresses some of 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 raw earth building materials. Unlike previous laboratory studies which have been mostly restricted to unconfined compression tests, this research focuses on the measurement of stiffness and strength inside a triaxial cell under variable levels of radial confinement.

2. MATERIALS AND METHODS

2.1. MATERIALS 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 soil [32] together with the recommended lower and upper limits according to current guidelines for the manufacture of compressed earth bricks [33-35].

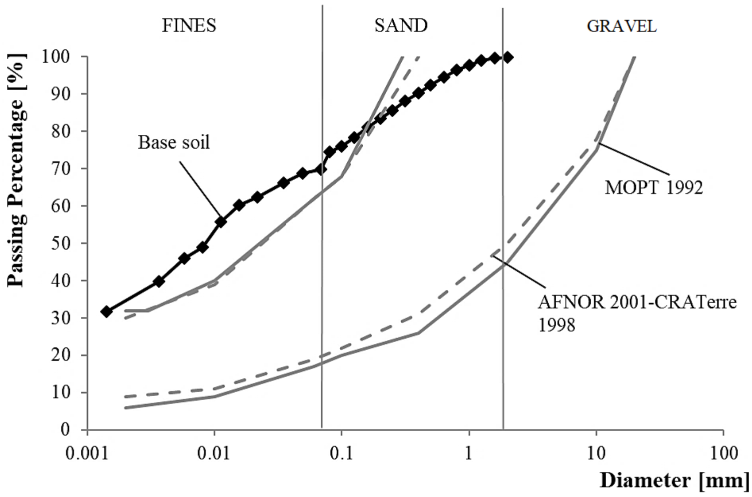


Figure 1: Particle size distribution of the base soil in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and MOPT [35] (after Cuccurullo et al. [32]).

The main properties of the base soil, including the Atterberg limits measured on the finer fraction (i.e. the fraction smaller than 0.400 mm), were determined in a previous study [32] and are summarised in Table 1. Previous studies [36] have 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 indicates the material to be a low plasticity clay [32]. Figure 2 also indicates that the soil fits inside the recommended plasticity regions 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		

Specific gravity G_s (-)	2.65	Goethite, Muscovite, Orthose, Kaolinite, Quartz, Calcite

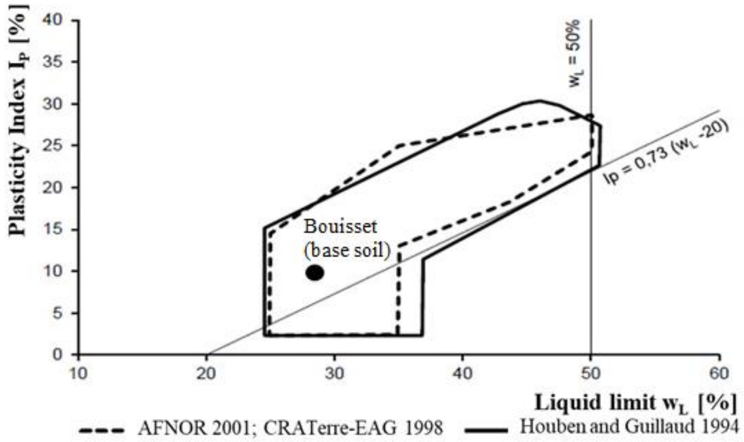


Figure 2: Plasticity properties of the base soil in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and Houben and Guillaud [37] (from Cuccurullo et al. [38]).

As with previous studies (e.g. [32]) 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. Figure 3 shows the particle size distribution of the added silica sand, whose grading is monodisperse with grain dimensions between 0.06 and 2 mm.

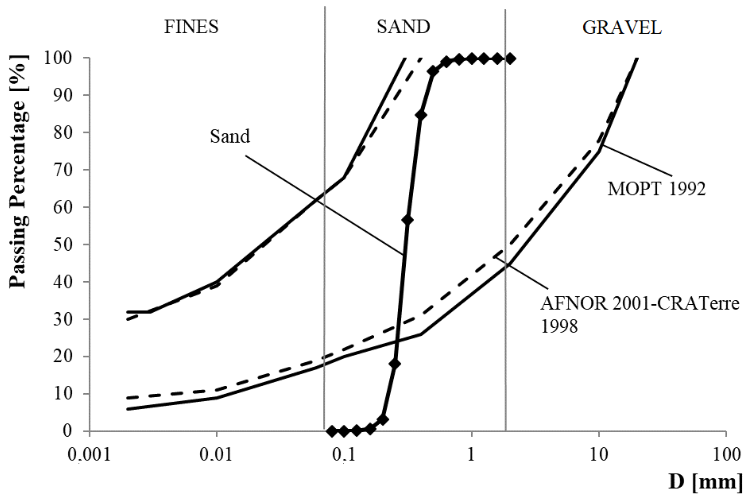


Figure 3: Particle size distribution of added sand in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and MOPT [35] (after Cuccurullo et al. [32]).

Table 2 summarizes the composition of the two earth mixes considered in this study, i.e. earth mix 1 that is the base soil and earth mix 2 that is a blend of the base soil and silica sand. Figure 4 shows the particle size distributions of the two mixes in relation to the recommended limits for the manufacture of compressed earth bricks [33-35] and 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 value. Conversely, earth mix 2 exhibits a poorly-graded particle size distribution, which cuts through the admissible band, and a clay content corresponding to the minimum 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 compliant with existing recommendations.

Table 2: Composition of the two earth materials (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

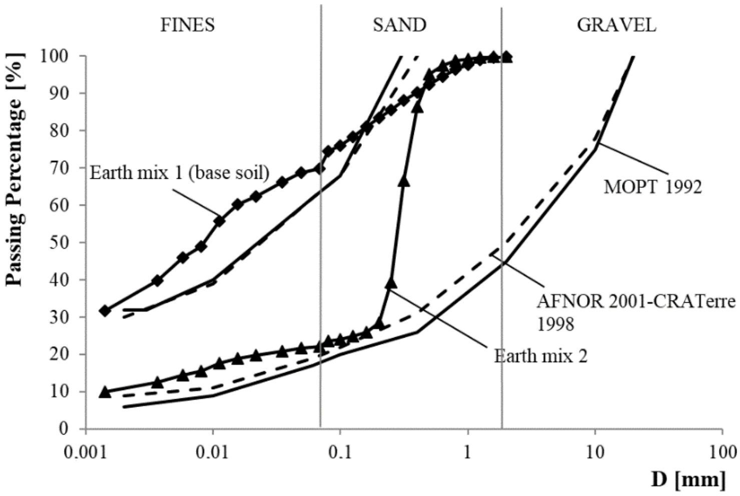


Figure 4: Particle size distribution of earth mixes in relation to existing recommendations for the manufacture of compressed earth bricks by AFNOR [33]; CRATerre-EAG [34] and MOPT [35] (after Cuccurullo et al. [32]).

2.2 EARTH COMPACTION

Figure 5 presents the standard Proctor compaction curve for earth mix 1 as previously determined in [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 defined by zero water content and a dry density equal to that of the 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 hyper-compaction curves of earth mixes 1 and 2 under a large static pressure of 100 MPa [32]. The hyper-compacted earth was vertically compressed inside a 50 mm diameter cylindrical mould using a load-controlled Zwick/Roell Amsler HB250 press with a capacity of 250 kN by two cylindrical pistons at the top and bottom of the sample. This double compression mechanism increases 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 of the sample. This happens because, during double compression, the friction between the earth and mould creates two opposite gradients of compaction stress that extend from each sample extremity to the middle section. Instead, during single compression, the same friction generates a single gradient of compaction stress that extends over a larger distance between the two extremities of the sample. Additional details of this procedure are available in Cuccurullo et al. [32] and Bruno [27].

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

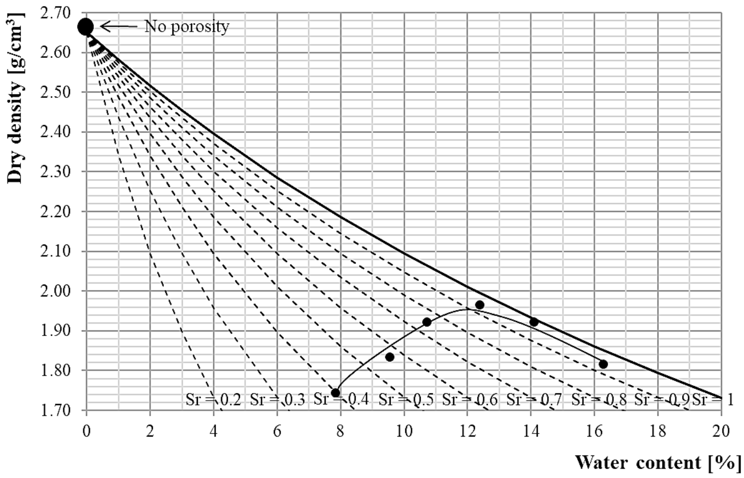


Figure 5: Standard Proctor compaction curve for earth mix 1 (after Cuccurullo et al. [38]).

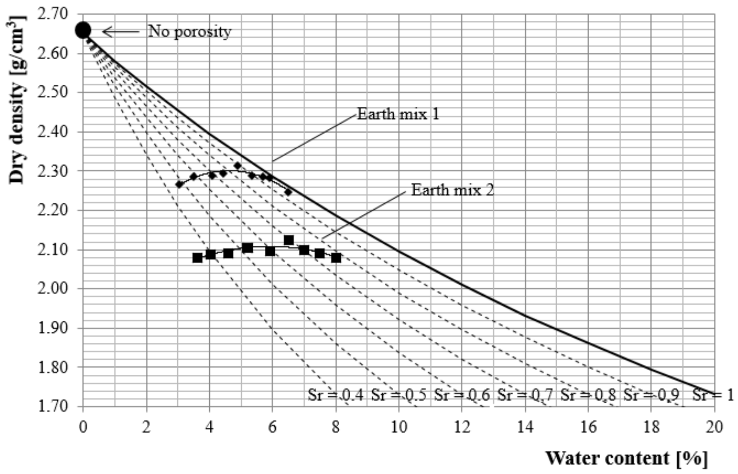


Figure 6: Hyper-compaction curves, corresponding to the application of a static pressure of 100 MPa, for earth mixes 1 and 2 (after Cuccurullo et al. [32]).

2.3 TRIAXIAL TESTING PROGRAM

Earth samples of 50 mm diameter and 100 mm height for triaxial testing were manufactured by one-dimensional static compaction under either an equivalent Proctor load or at 100 MPa (hyper-compaction).

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 value of the Proctor dry density (see Figure 5). During compaction, care was taken in scarifying the surface of each layer before compacting the next. Hyper-compacted samples of both earth mixes 1 and 2 were 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. Both hyper-compacted and Proctor compacted samples were statically compacted.

Twelve samples of each one of the three materials (i.e. Proctor compacted earth mix 1, hyper-compacted earth mix 1 and hyper-compacted earth mix 2) were manufactured and subsequently 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 relative 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. Equalisation was assumed to be complete when the sample mass changed less than 0.1 % over at least one week, which took generally 15 days. The total suction, ψ at equilibrium was calculated from the imposed values of temperature, T and relative humidity, RH according to Kelvin's law as:

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

where R is the gas constant and V_m is the molar volume of water. The values of total suction calculated using Equation 1 are shown in Table 3.

The diameter, height and mass of the equalised samples were measured prior to testing inside the triaxial cell. At the end of the test, three earth fragments of about 50 grams each were taken at the top, middle and bottom of the specimen to determine the water content according to the French norm NF P 94-050 [40]. The water content was calculated as the average of these three measurements, which were generally similar, thus confirming the uniformity of moisture content across the sample. From the measured sample volume V, mass W, water content w and specific gravity of solid particles G_s, the corresponding values of bulk density ρ_b, dry density ρ_d, void ratio e, degree of saturation S_r and porosity n were calculated (assuming a specific water weight $\gamma_w = 1\ kN/m^3$) as:

$$\rho_b = \frac{W}{V} \tag{2}$$

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

$$n = 1 - \frac{\rho_d}{\rho_w\, G_s} \tag{4}$$

$$S_r = \frac{w\ \rho_d}{n\ \rho_w} \tag{5}$$

Table 3 summarises the average values of these parameters for each set of three samples. It is here assumed that the sample moisture content did not change during the test and, therefore, the values in Table 3 coincide with those at the end of the test. Due to experimental problems, reliable measurements of water content could not be obtained for the hyper-compacted samples of earth mix 2 at humidity levels of 62% and 95%, which explains the gaps in Table 3. The value of total suction for 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: Samples properties after oven-drying or equalisation at different humidity levels.

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]**
Hyper-compacted 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
Hyper-compacted 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

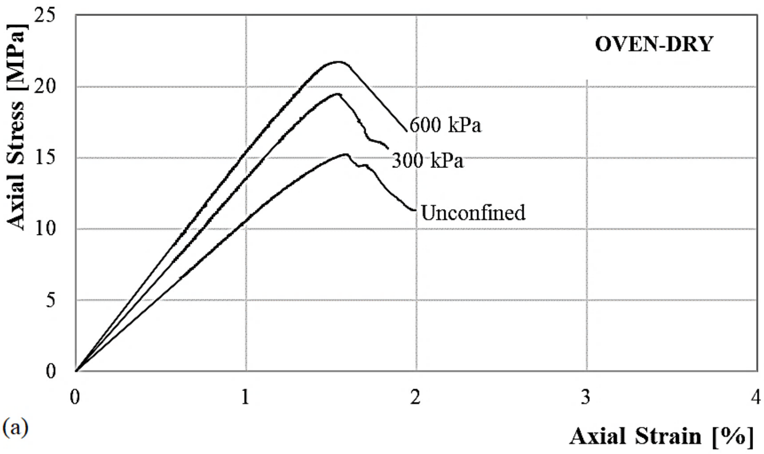
Inspection of Table 3 indicates that the equalisation of earth mix 1at distinct humidity levels produces different degrees of saturation and this is significantly more evident for the hypercompacted samples than for the Proctor compacted ones. The sensitivity of degree of saturation to ambient humidity is therefore likely to be higher for earth building materials than standard geotechnical fills due to the higher dry density of the former materials compared to the latter ones. Moreover, different degrees of saturation correspond to distinct magnitudes of inter-particle capillary bonding and, therefore, distinct levels of material strength and stiffness. To explore this aspect, the three materials equalised at different humidity levels were sheared inside a triaxial cell with an axial displacement rate of 0.06 mm/min. In particular, the three samples of each set were sheared under different radial stresses of 0 kPa, 300 kPa and 600 kPa, respectively, to investigate the effect of the lateral confinement of the earth inside thick walls. Throughout the 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 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.

Test results were subsequently processed to determine the values of the initial Young's modulus and 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 compressive strength, where the material response is reasonably linear.

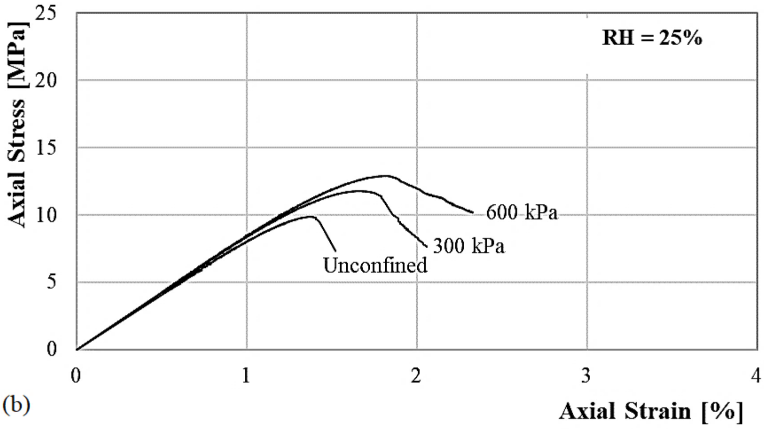
3 RESULTS AND DISCUSSION

Figure 7 shows the stress-strain curves measured during the triaxial tests on the hyper-compacted samples of earth mix 1 equalised at distinct humidity levels under different confining pressures. Figure 7 shows that, at all humidity levels, the peak strength increases by a margin of between 30% and 50% as the confining stress increases from zero to 600 kPa, which highlights the beneficial effect of lateral confinement on material strength.

Inspection of Figure 7 shows that, at a given confining pressure, the peak stress increases as the ambient humidity decreases. This 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, which bond earth grains together and therefore improve the mechanical characteristics of the material [5,41]. The largest strength levels, in excess of 20 MPa, were measured on dry samples. Dry samples should by definition contain no capillary water menisci at all and be, in principle, no different from water saturated samples and therefore exhibit the lowest values of strength. However, in reality, the residual presence of a small quantity of adsorbed inside the oven-dry samples, subjected to extremely high tensile stresses, firmly bond earth particles together. Inspection of Figure 7 also indicates that the response of the samples 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 considerable reduction of shear strength but also enhances the material ability to undergo plastic deformation before failure.


OVEN-DRY
Axial Stress [MPa]
Axial Strain [%]
600 kPa
300 kPa
Unconfined
0
5
10
15
20
25
0
1
2
3
4

(a)


RH = 25%
Axial Stress [MPa]
Axial Strain [%]
600 kPa
300 kPa
Unconfined
0
5
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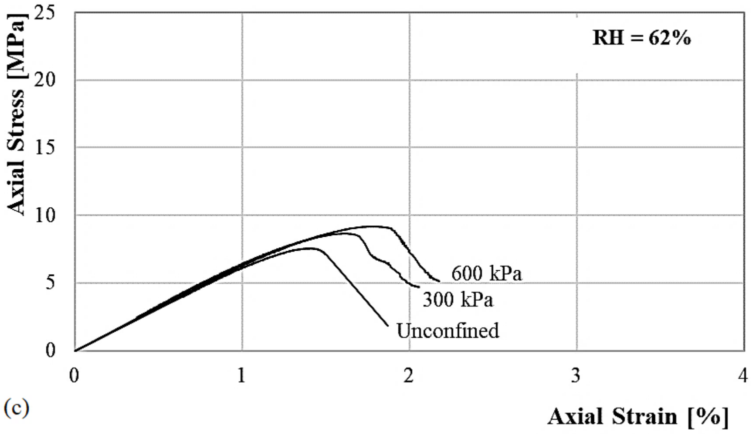
(b)


RH = 62%
Axial Stress [MPa]
Axial Strain [%]
600 kPa
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Unconfined
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(c)

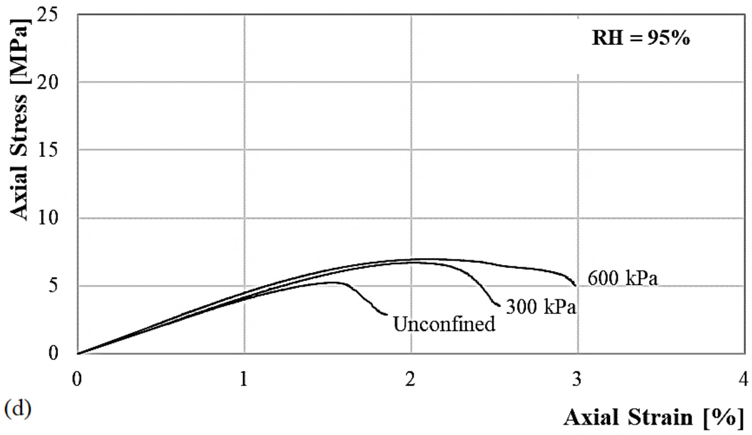
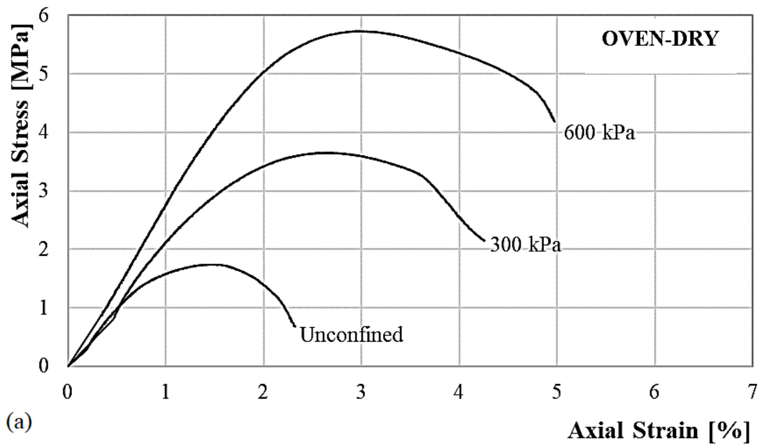


Figure 7: Results from triaxial tests on the hyper-compacted earth mix 1 at different confining pressures and distinct humidity levels: oven-dry (a), 25 % (b), 62 % (c), 95 % (d).

Figure 8 shows the stress-strain curves measured during the triaxial tests on the hyper-compacted samples of earth mix 2 where, as before, peak stress 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 significantly lower than the corresponding maximum of earth mix 1. Inspection of Figure 8 also confirms the change in mechanical behaviour from fragile to ductile as relative humidity grows, thus increasing the ability of the material to deform plastically before failure. The beneficial effect of lateral confinement on the mechanical response of the material is more marked than in the previous case, with an increase of strength that can be six-fold as the radial stress grows from zero to 600 kPa at constant humidity.

The comparison of the triaxial response 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, despite both mixes are hyper-compacted and exhibit particle size distributions that are admissible according to existing guidelines (Figure 4). Interestingly, the only difference between these two earth mixes relates to the dispersion of the 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 grading difference is also reflected by the significantly different levels of dry density produced by an identical compaction effort (Figure 6). This means that very different mechanical responses can be obtained inside the admissible grading band of Figure 4 and that a fine well-graded earth can produce considerably higher strength levels than a coarse poorly-graded earth. Therefore, for a fixed compaction effort, coarser materials will not always generate higher levels of strength, as frequently implied, because of the role of particle grading, whose importance may even outstrip that of average particle size.



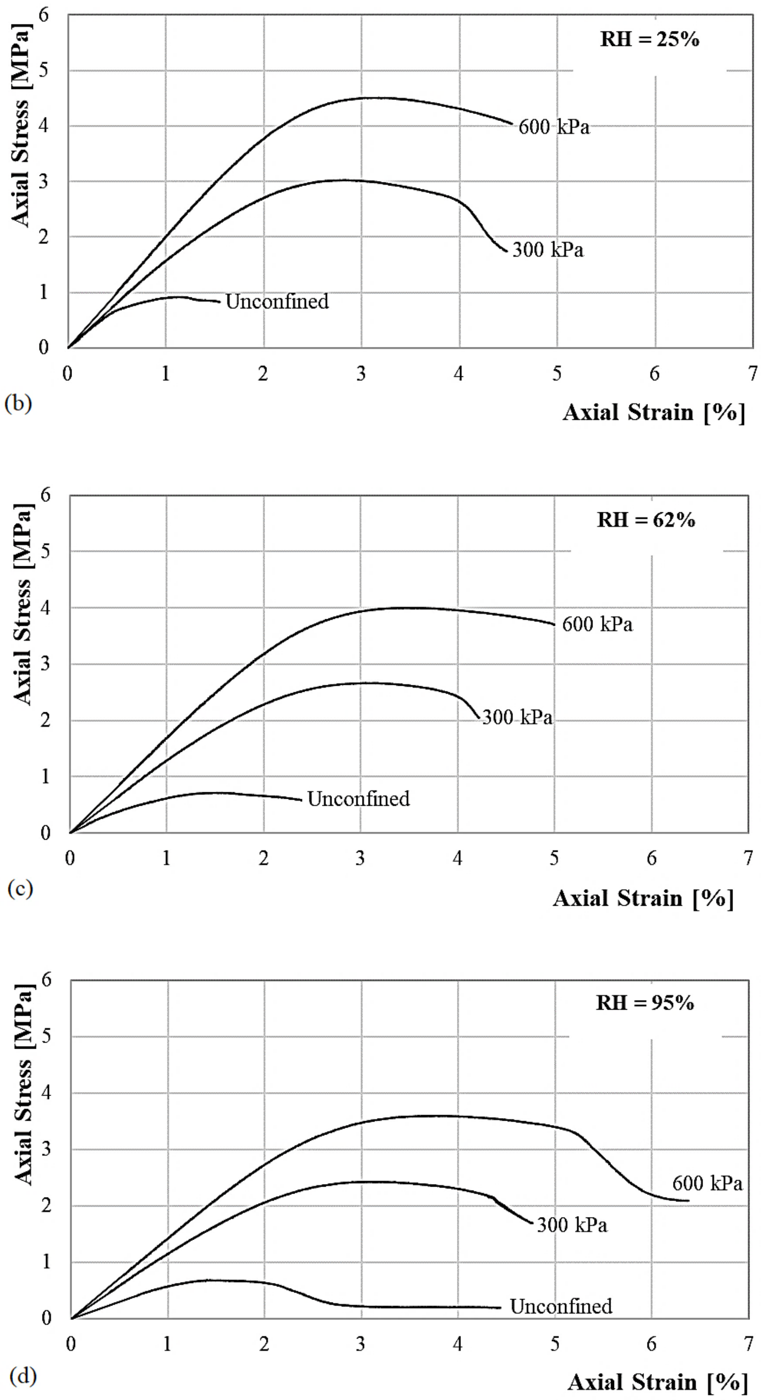
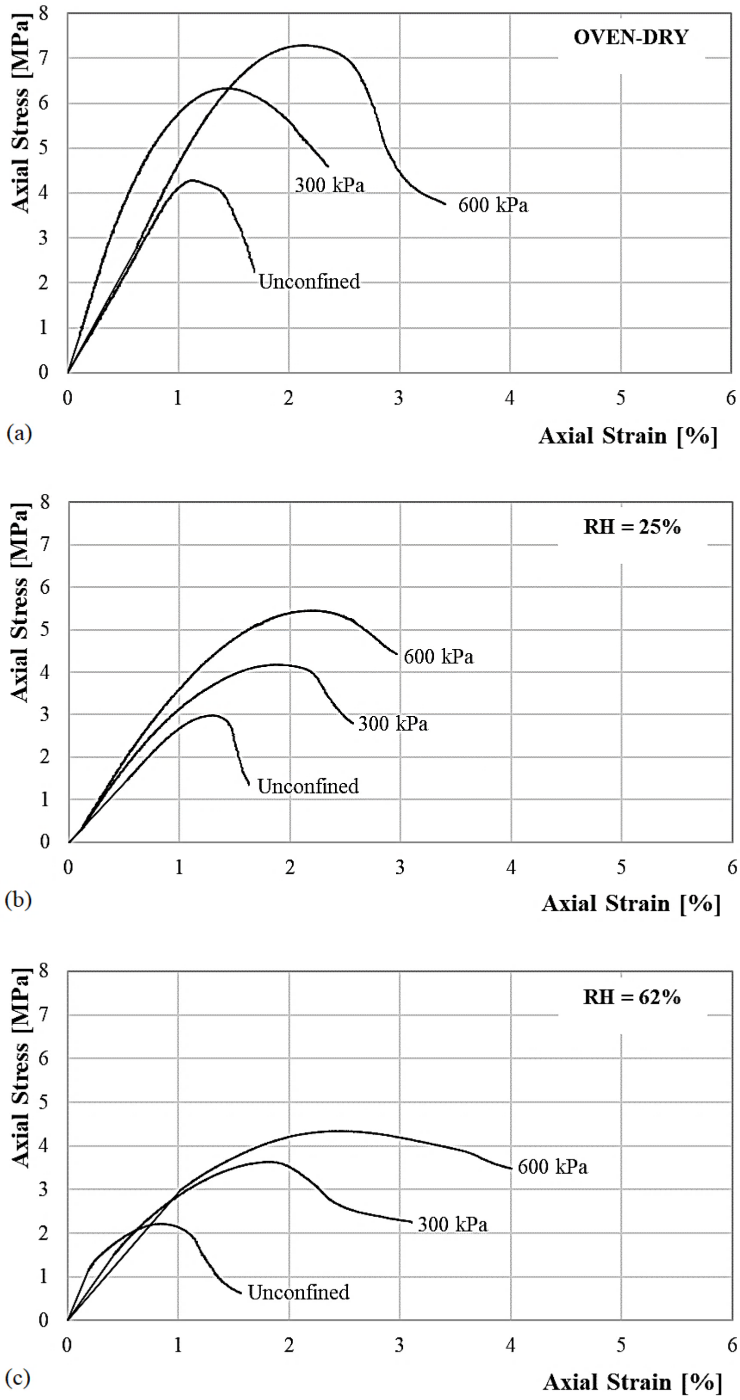


Figure 8: Results from triaxial tests on the hyper-compacted earth mix 2 at different confining pressures and distinct humidity levels: dry (a), 25 % (b), 62 % (c), 95 % (d).

Figure 9 shows the stress-strain curves of the triaxial tests on the Proctor samples of earth mix 1 where similar conclusions can be drawn regarding the effect of ambient humidity on material strength. Inspection of Figure 9 indicates a maximum three-fold increase of strength with growing radial stress from 0 to 600 kPa at constant humidity, which corresponds to an intermediate response with respect to the previous two cases. Most importantly, Figure 9 indicates that the strength levels measured on the Proctor compacted samples of earth mix 1 are generally higher than those recorded on the hyper-compacted samples of earth mix 2 (Figure 8), despite the former samples exhibiting 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 strength levels that are higher than those of a considerably denser material with a poorly-graded distribution. This confirms, once again, the key role of particle grading in enhancing material strength, a role which appears even more significant than that of material density. This is an important conclusion that has not found adequate space in previous studies, which have instead focused on compaction as the main means of improving mechanical strength.

Finally, a comparison between the Proctor compacted (Figure 9) and hyper-compacted (Figure 7) samples of earth mix 1 shows that strength levels are significantly higher in the latter than the former. This is an expected result as, for a given particle size distribution, a stronger compaction effort generates a larger density and hence higher strength levels. Perhaps less intuitive is the greater ductility of the Proctor compacted samples compared to the hyper-compacted ones, although the trend is consistent with the observed increase of ductility with decreasing strength at higher levels of humidity.



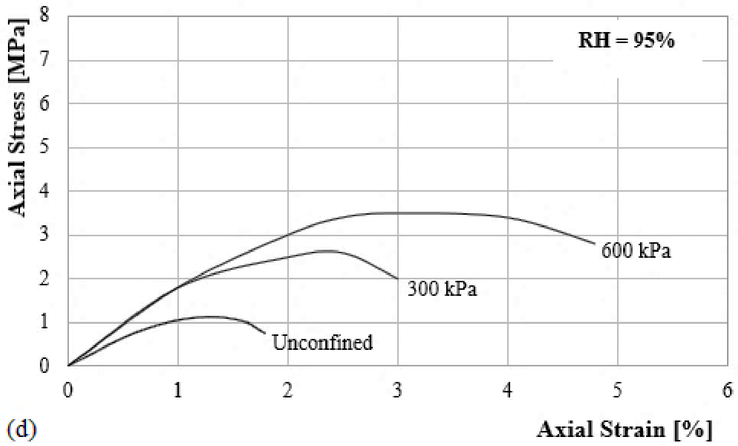
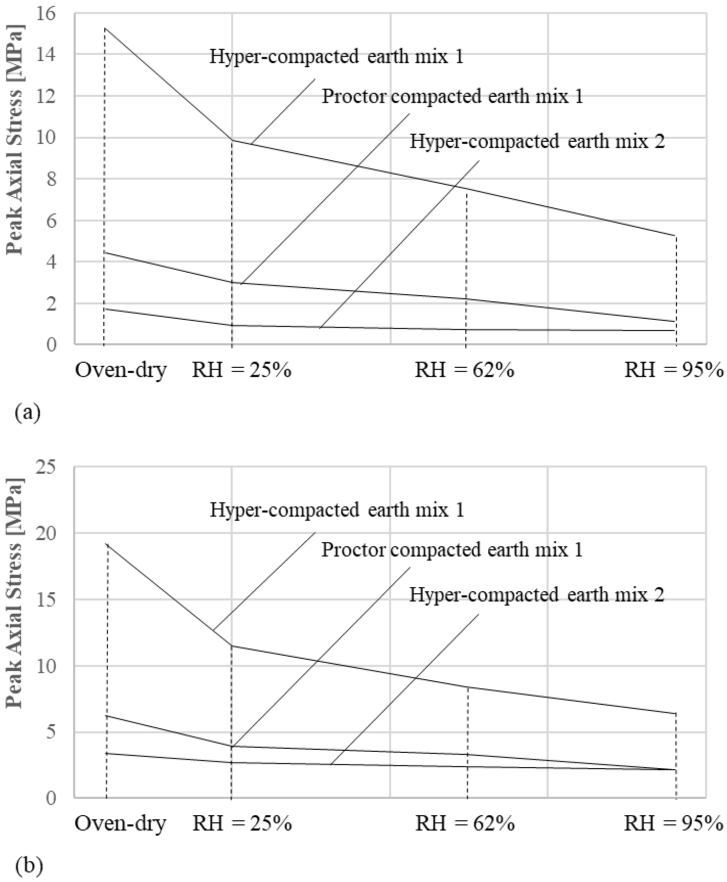
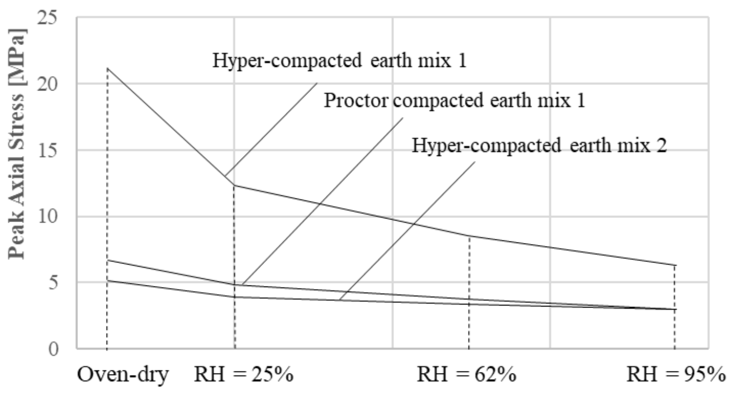


Figure 9: Results from triaxial tests on the Proctor compacted earth mix 1 at different confining pressures and distinct humidity levels: dry (a), 25 % (b), 62 % (c), 95 % (d).

To help readability, Figure 10 shows the evolution of maximum axial stress as function of relative humidity at different confining pressures of 0 kPa, 300 kPa and 600 kPa.





(c)

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

The effect of degree of saturation on mechanical characteristics can be synthetically described by comparing, for each material, the strength and stiffness envelopes at constant levels of ambient humidity.

The strength envelopes are obtained by plotting the values of peak deviator stresses q, measured from three tests at each humidity level, against the corresponding values of mean stresses p. These experimental values 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 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 hyper-compacted earth mix 1, hyper-compacted earth mix 2 and Proctor compacted earth mix 1, respectively. Similarly, Tables 4, 5 and 6 summarise the values of the strength parameters of the hyper-compacted earth mix 1, hyper-compacted earth mix 2 and Proctor compacted earth mix 1, respectively.

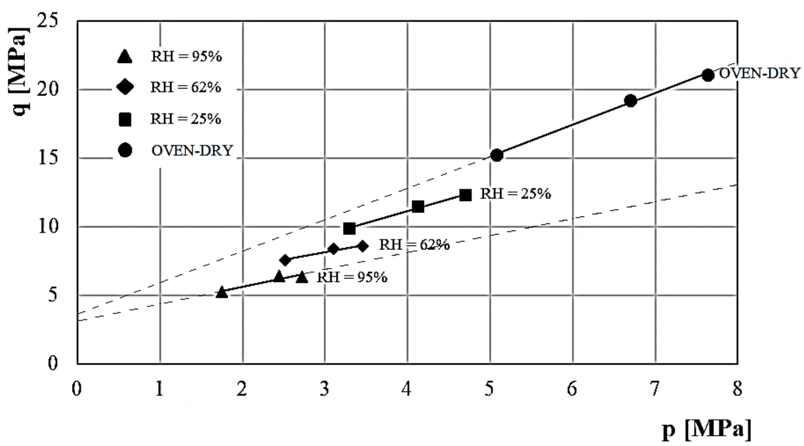


Figure 11: Strength envelopes of hyper-compacted earth mix 1 at different humidity levels.

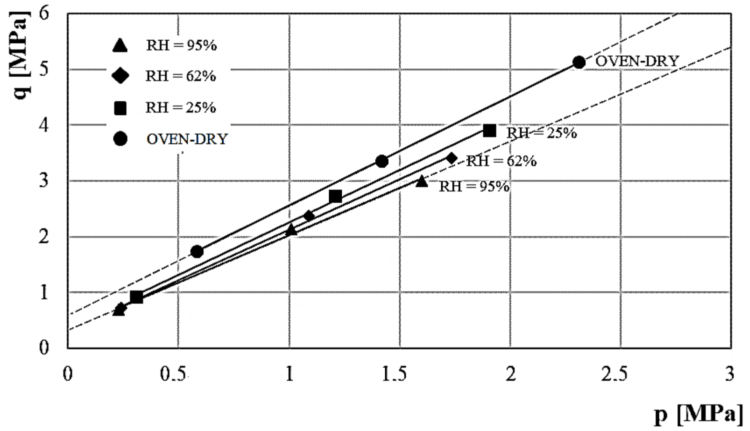


Figure 12: Strength envelopes of hyper-compacted earth mix 2 at different humidity levels.

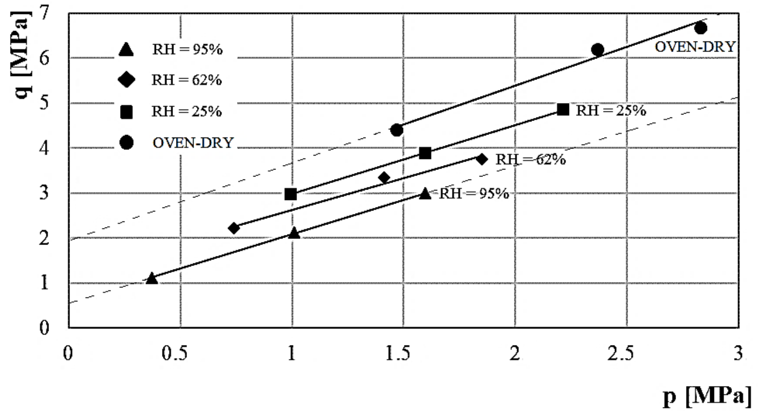


Figure 13: Strength envelopes of Proctor compacted earth mix 1 at different humidity levels.

Table 4: Strength parameters of hyper-compacted 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 hyper-compacted 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 hyper-compacted samples than in the Proctor compacted ones. Among the hyper-compacted 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 which is consistent with 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 hyper-compacted samples (Tables 4 and 5) than for the Proctor compacted ones (Table 6). This is also shown graphically by Figures 11 and 12 where the strength envelopes of the hyper-compacted materials tend to converge towards a point as the mean stress reduces towards zero. The trend is clearest for the hyper-compacted earth mix 1, whose cohesion is approximately constant at all humidity levels (Table 4), apart from a slight 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 hyper-compacted earth mix 1, hyper-compacted 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 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 material strength, an increase of ambient humidity produces a decrease of stiffness. The effect of lateral confinement is less evident than in the case of material strength as the stiffness remains relatively constant with growing radial stress at constant humidity. Only in the case of the oven-dry samples is a clear increase of stiffness with growing radial confinement observed. In general, however, 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.

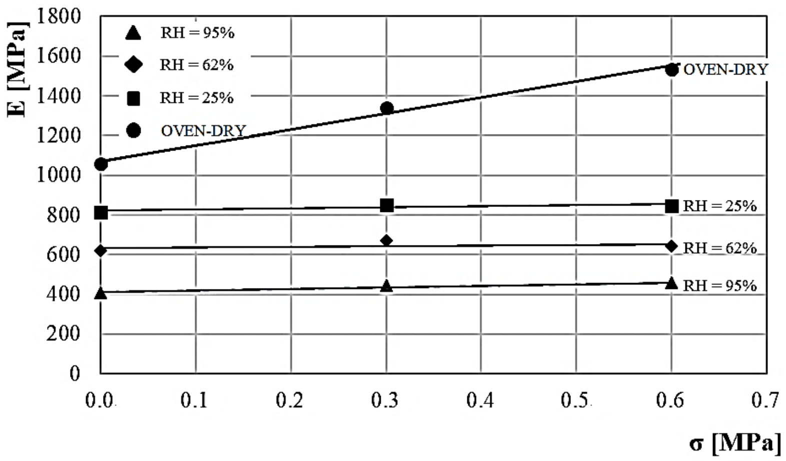


Figure 14: Stiffness envelopes of hyper-compacted earth mix 1 at different humidity levels.

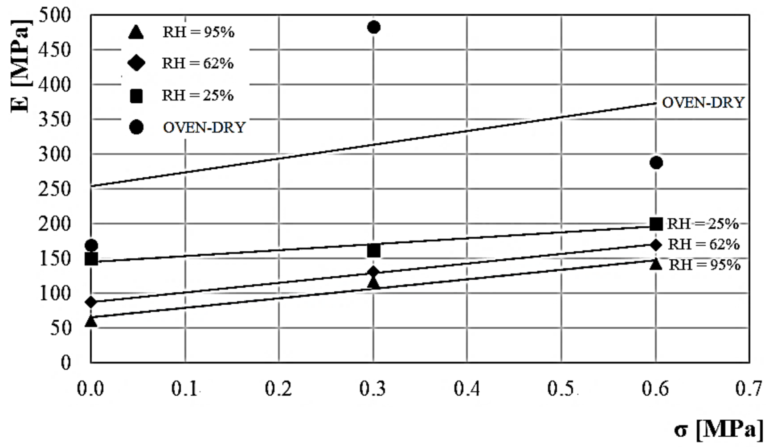


Figure 15: Stiffness envelopes of hyper-compacted earth mix 2 at different humidity levels.

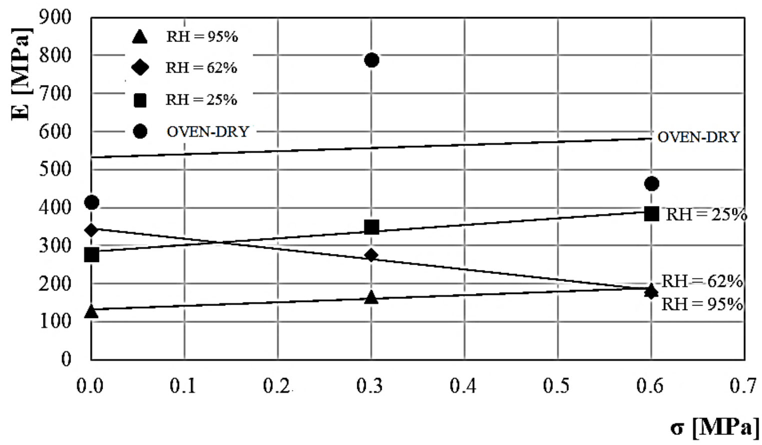


Figure 16: Stiffness envelopes of Proctor compacted earth mix 1 at different humidity levels.

4 CONCLUSIONS

This paper has presented an experimental investigation of the simultaneous effects of particle grading, dry density and ambient humidity on the mechanical behaviour of earth building materials. Three earth building materials have been manufactured from soils with markedly distinct particle size distributions and compacted under significantly different efforts. In general, for a given earth mix, the variation of the hydro-mechanical properties with ambient humidity strongly depends on the dry density of the material. This emphasizes the specific nature of earth building materials, which tend to be much denser than standard geotechnical fills.

Particle grading has emerged as a key parameter governing the mechanical performance of earth materials, whose influence appears even more significant than that of dry density. The present study has shown that the strength and stiffness of the Proctor-compacted earth mix 1 are generally higher than those of hyper-compacted earth mix 2 despite the former material having a markedly lower density. It may be a surprise that an earth material of relatively low density exhibits higher levels of strength and stiffness than those of a considerably denser one, even more so if both earth mixes exhibit index properties (i.e. particle size distribution and plasticity characteristics) that comply with current building recommendations. This apparently counterintuitive result can be explained by the different particle grading of the two earth mixes, which is more uniform in the case of earth mix 1 compared to earth mix 2. The role of earth grading has often been overlooked but instead appears key for achieving high levels of strength and may even transcend the influence of average particle size and compaction effort. The findings of this study have therefore prompted further research on the optimisation of earth mixes for building applications starting from a revision of current guidelines about the identification of suitable index properties for the base soil.

In line with previous investigations, the present study has also found that: a) the material ductility (i.e. the ability of the material to undergo significant plastic deformation before failure) tends to increase with decreasing strength, b) the mechanical characteristics of a given earth mix tend to improve with growing dry density and c) the mechanical characteristics of a given earth mix, compacted at a given density, tend to deteriorate under high levels of ambient humidity. Regarding this last point, an increase of ambient humidity produces an augmentation of degree of saturation and a consequent reduction of strength and stiffness, which is accompanied by an increase of ductility.

Finally, at all humidity levels, strength increases significantly as the confining stress becomes larger, which highlights the beneficial effect of lateral confinement inside building walls. The magnitude of this increase depends on both particle grading and density, though the largest improvement of strength is obtained, in this case, for the poorly graded earth mix 2 whose strength increases up to six-fold when the radial stress grows from zero to 600 kPa. Conversely, material stiffness remains generally constant when radial stress grows at constant humidity.

5 ACKNOWLEDGEMENTS

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