Mechanical characterization of lime-stabilized rammed earth: lime content and strength development

Fernando Ávila[a,*], Esther Puertas[a], Rafael Gallego[a]

[a] *Dept. of Structural Mechanics and Hydraulic Engineering, University of Granada, Av. Fuentenueva, 18001 Granada, Spain*

Abstract

Earth construction techniques, such as rammed earth, are present worldwide due to the availability of the material and its mechanical performance. Today they are also attracting attention as an environmentally friendly way of building, although additivation is usually needed. Lime stabilization is an interesting option with long tradition, well-known capacity to improve soil properties and limited environmental impact. This study evaluates the effect of increasing lime contents in the compressive strength and stiffness of rammed earth, and analyses the strength development process of the material. Carbonation depth and ultrasonic pulse velocity are also evaluated due to their relationship with the mechanical behavior. The results show that 12 % lime maximized the compressive strength and stiffness of the rammed earth material; the strength was mostly developed during the first month but needs over a hundred days to be fully developed. A good linear correlation between the ultrasonic pulse velocity and the compressive strength is observed.

Keywords: rammed earth, lime stabilization, strength development, mechanical characterization, carbonation, ultrasonic pulse velocity

1. Introduction

The construction sector, nowadays, is well aware of the severe environmental impact caused by its activities, including resource consumption, waste generation and pollution. This situation, which is getting worse over the years due to the increasing demand for housing as the global population grows, has drawn the attention of builders and researchers to non-conventional construction techniques and materials with lower environmental impacts. One such technique, with very long tradition and a promising future, is rammed earth (RE) [1–4].

*Corresponding author

Email addresses: favila@ugr.es (Fernando Ávila), epuertas@ugr.es (Esther Puertas), gallego@ugr.es (Rafael Gallego)

RE building technique consist of compacting, between formwork, 7 to 15 cm-thick layers of sandy soil mixed with a certain amount of water in order to create walls with a thickness of 30–60 cm [5–8]. Natural soil can be directly used to build RE structures, leading to the so-called unstabilized rammed earth (URE), with clay acting as the only binder; but when higher strength or durability are required it is common to add different kinds of additives to the mixture. This technique is called stabilized rammed earth (SRE).

One of the additives with longest tradition for rammed earth stabilization is lime, existing several examples of historic constructions made of lime-stabilized rammed earth (LSRE) [6, 9–13]. The RE used in these heritage buildings usually contained very significant percentages of lime, e.g., between 10 % and 15 % in the medieval walls of Seville (Spain) [14] and in traditional RE houses in Southern Portugal [15], 20 % in the Alcazaba Qadima and the Alhambra of Granada (Spain) [10, 16], also 20 % in the Saadian sugar refinery of Chichaoua (Morocco) [9], and ca. 25 % in the Fujian Tulou (China) [17] or in the Cáceres city walls (Spain) [14].

There is also a broad consensus that lime stabilization improves the mechanical and hydraulic behavior of soils [18–22]. When lime is added to a soil, the concentration of Ca^{2+} and OH^- increases due to the hydration reaction of lime. This generates the flocculation of particles (affecting soil plasticity) and increases the pH, causing the dissolution of silica and alumina from soil minerals, which react with calcium forming calcium silicate (or aluminate) hydrates that cement soil particles and increase the mechanical performance of the material [19, 23, 24].

However, and despite its historical use, today lime has been superseded by cement as the most common stabilizer for rammed earth [25], and as a consequence there is a lack of scientific research specifically analyzing the effects of lime stabilization in the mechanical properties of RE. Ciancio et al. [7] carried out a study evaluating the optimum lime content for LSRE, obtaining a value equal to 4 % by weight, but lime contents greater than 6 % were not considered. Da Rocha et al. [26] also analyzed LSRE materials, from 3 %wt to 9 %wt, concluding that the uniaxial compressive strength increased with increasing lime contents and indicating the need of long curing times. Also Canivell et al. [27] and Arto et al. [28] have recently evaluated the compressive strength and fracture energy, respectively, of RE materials stabilized with high percentages of lime.

Understanding the mechanical behavior of LSRE is essential in order to properly preserve the large number of heritage buildings made with this technique, but also because of its potential benefits in the development of an environmentally-friendly way of constructing. Lime is considered to be a much less energy-intensive binder compared to the frequently used Portland cement [7], as its manufacturing temperature is significantly lower (ca. 900 °C as opposed to 1 500 °C) [29], which reduces the CO_2 emissions during production. It is estimated that ca. 0.9 t of CO_2 are produced per tonne of cement, while the manufacturing process of lime produces less than 0.7 t of CO_2 per tonne of lime [30–33]. In addition, the carbonation reaction (through which lime uptakes atmospheric CO_2) during the lifetime of the building can counterbalance the carbon emissions generated in the manufacturing and transportation process, leading to a reduction of the net carbon footprint of lime-stabilized materials [29, 34, 35].

Against this background, this study presents an analysis of the effect of lime stabilization in the mechanical behavior of rammed earth, evaluating the compressive strength and stiffness of the material with diverse lime contents and analyzing its strength development process.

2. Materials

2.1. Soil

The main source material used for the RE in this study was a natural soil from a quarry in Padul (Granada, Spain), classified according to the European Soil Classification System (ESCS, ISO 14688-2:2018) as clayey well-graded sand, after been passed through a 10 mm sieve in order to remove the coarser particles. The particle size distribution of the resulting earthen material is shown in Figure 1, been in agreement with recent studies regarding rammed earth stabilization [36–38] and fitting withing the envelope recommended by Houben et al. [39], widely accepted for URE construction and frequently used also for SRE [25]. The soil had chloride and sulfate contents lower than 0.002 % and was free of organic matter and light contaminants. This soil can be considered to be representative of the material traditionally used in RE construction in Southern Spain [13, 14, 16, 28, 40].

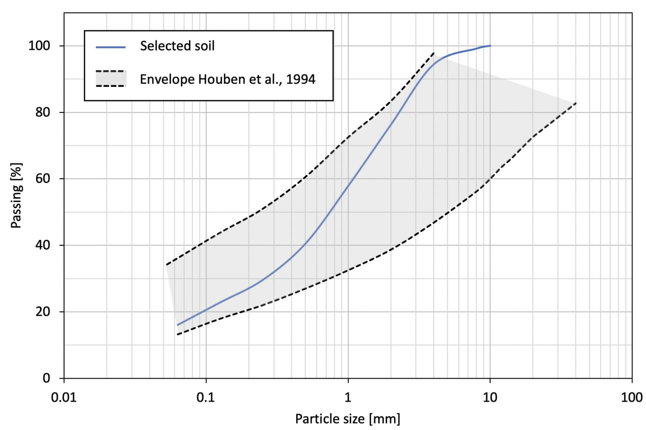

Figure 1: Particle size distribution of the soil.

2.2. Lime

Natural hydraulic lime with minimum compressive strength of 3.5 MPa at 28 days, referred to as NHL 3.5 according to European standard EN 459-1:2015, was used as stabilizer. The main components of NHL are portlandite, reactive silicates and aluminates formed during calcination from the reaction of crushed limestone containing clay or other impurities. Table 1 shows the most relevant chemical and physical properties of the lime used in the present study.

Parameter	Avg. value
SO_3 [%]	1.7
Free lime, $Ca(OH)_2$ [%]	30
Free H_2O [%]	0.7
Residual at 90 µm [%]	5.7
Residual at 200 µm [%]	0.8
Bulk density [kg/dm^3]	0.671
Real density [kg/cm^3]	2.51
Blaine value [cm^2/g]	8500
Setting time [min]	296
End of taking [min]	438
Compressive strength at 28 days [MPa]	4.8

Table 1: Chemical and physical properties of the natural hydraulic lime used in the study, as indicated by the manufacturer.

3. Experimental procedure

3.1. Specimen preparation

In order to perform the experimental tests, 10 cm-side cubic LSRE specimens were manufactured. It is generally assumed that the size and shape of the samples may affect the mechanical properties obtained [5], although the relation between these parameters is still unclear and it is out of the scope of this paper. Similar geometries to the one used for the samples in the present study have been previously used by several authors [3, 27, 36, 41–44].

In order to define the correct amount of water to be added to the mixture, Modified Proctor tests (UNE 103501 [45]) were performed on specimens with diverse lime contents. Modified Proctor is a widely established and easily repeatable test that provides a compactive effort very close to the one that might be applied in the construction of a real wall [7, 41]. It was observed that greater amounts of water were needed in order to obtain the maximum dry density (MDD) with increasing lime contents, that is to say, the optimum moisture content (OMC) linearly increased with the lime content. However, this increase in the OMC with the lime content is quite small (equal to ca. 3 %), as it was noted by Ciancio et al. [7], that reported variations lower than 2 % for lime contents between 0 % and 6 %. Furthermore, other authors [26, 46, 47] propose using constant OMC regardless the lime content, as they indicate that the variation is negligible. The results of the compaction tests also showed that the MDD of the LSRE decreases with the increase in lime content, in a very pronounced way for small lime contents and then gradually stabilizing. The variation of the OMC and MDD as a function of the lime content is shown in Figure 2.

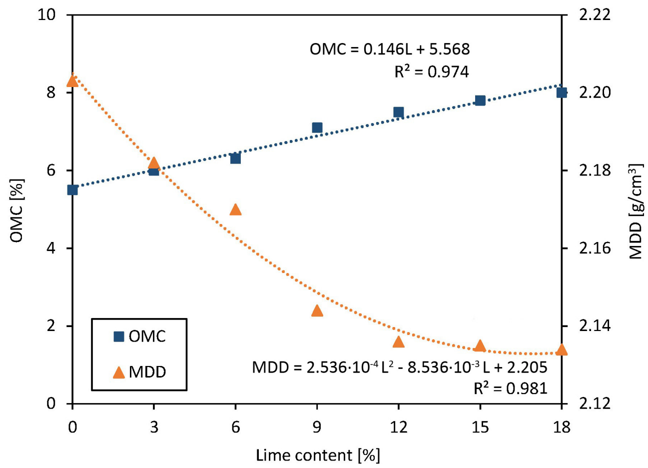

Figure 2: Optimum moisture content and maximum dry density, from Proctor test, as a function of the lime content.

The material was prepared by uniformly mixing the natural soil with a certain amount of lime. Water was added to the mixture until reaching a water content equal to the OMC+2 %, following the recommendations of Walker et al. [4] and the New Zealand Standard NZS-4298 [48].

The mixture was then poured into cubic molds and compacted by layers of ca. 2 cm, so each specimen was made up of five earth layers. The small thickness of the layers was chosen in order to provide a more uniform compaction and to reach a high compaction level by manual means. The material was compacted to 98 % of the MDD, according to NZS.4298 [48]. Once the upper layer was compacted and its surface smoothed, the samples were carefully removed from the mold and stored on wire racks, so all the faces could be in contact with the environment. The specimens were cured under constant conditions of about 25 °C and 40 % relative humidity, replicating common natural ambient conditions in Southern Spain.

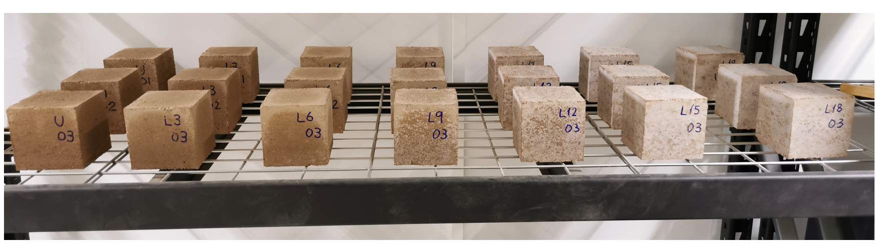

Figure 3: Some of the LSRE specimens, with different lime contents, stored on wire racks during the curing period.

3.2. Experimental evaluation

The uniaxial compressive strength (UCS) and stiffness of the LSRE specimens were determined performing uniaxial compression tests, applying a homogeneously distributed load on the upper face of the sample, perpendicular to the direction of the earth layers. The tests, in the absence of specific standards for RE testing, were performed according to European Standard EN 12390-3 "Testing hardened concrete. Part 3: Compressive strength of test specimens" [49]. A linear variable differential transformer (LVDT) was used to measure the longitudinal displacements for the calculation of the stiffness modulus. In the first part of the study, UCS tests were carried out on specimens with increasing lime contents, from 0 % to 18 % every 3 %.

Once the results were evaluated, more samples were manufactured with the lime content that led to a better mechanical performance (i.e. 12 %). These specimens were subjected to UCS tests at different curing times, from 2 to 100 days, with a minimum of three specimens per curing time. The time intervals between the tests were smaller during the first weeks (every 2–5 days), as a greater variation of the mechanical properties was expected –and observed–, and longer for older specimens (every 10 days approx.). After the compression tests, the depth of the carbonation front in the specimens was measured by using phenolphthalein solution 1 % in ethanol as indicator, carefully cleaning the surfaces before testing using a compressed air gun. The carbonation depth is measured using a sliding gauge at 3 to 5 equidistant points on each of the four faces on a slice of the specimen, perpendicularly to the exposed surface of the cube, as indicated in standard EN-12390-12 [50]. The carbonation depth considered to be representative of the specimen was obtained as the average of those measurements.

During the curing period, the specimens were periodically weighted to control the loss of moisture, and subjected to ultrasonic pulse velocity (UPV) tests. UPV method is one of the non-destructive testing techniques whit a longest tradition for assessing the mechanical properties and inner cracks of building materials. A ultrasonic device, consisting of a transmitting and a receiving transducer, was used to measure the time of pulse of ultrasonic waves over a known path length [51]. Although UPV method has been widely used for concrete, metal of wooden materials, only a few recent studies have applied it to determine RE mechanical properties [27, 43]. The UPV was measured for the manufactured LSRE specimens in a direction parallel to the earth layers.

4. Results and discussion

4.1. Stress-strain behavior

The compressive behavior of RE specimens was obtained from the compression tests carried out according to standard EN 12390-3 [52], as mentioned above. This standard indicates that the results of the tests can be considered valid if all four exposed faces are cracked approximately equally, generally with little damage to faces in contact with the platens, as shown in Figure 4.

Figure 4: Satisfactory failures of cubic specimens, according to EN 12390-3 [52].

Stress-strain curves were obtained from uniaxial compression tests for the specimens with different lime contents after 28 days of curing. Figure 5 shows the stress-strain curves of all tested samples. It is possible to observe that, for almost all the specimens, at the beginning of the test, the material suffers significant strains for small load increments, while the earth particles are settling and so the fine grains fill the empty spaces between the coarser ones. Then, at ca. 0.01 mm/mm strain, the stiffness significantly increases and the material shows linear behavior until approximately 75 % of the maximum stress. This linear phase, however, also comprises plasticity due to the formation of microcracks, so it cannot be considered as linear-elastic [47, 53–55]. This is followed by a plastic phase with a reduction of the stiffness until maximum stress is reached, then crack propagation occurs rapidly until failure.

4.2. Compressive strength and stiffness

According to the evaluation of the stress-strain curves obtained from the experimental tests, the material shows a linear behavior approximately between 35 % and 75 % of the maximum stress, so the stiffness modulus (E) of the samples was calculated according to the following equation, which is based on the formulation proposed in ASTM C469 [56] for concrete samples, and used for rammed earth in previous studies [36, 38]:

$$E = (S_{75} - S_{35})/(\varepsilon_{75} - \varepsilon_{35}) \tag{1}$$

where S_{35} and S_{75} are the stresses corresponding to 35 % and 75 % of the maximum stress, respectively; and ε_{35} and ε_{75} are the longitudinal strains produced by stresses S_{35} and S_{75}, respectively.

The parameter E defined in Equation 1 is a secant stiffness modulus, following the recommendation of the aforementioned standard and Koutous and Hilali [47], which indicates that the secant modulus is the best parameter to describe the elastoplastic mechanical behavior of earthen materials. These authors also noted that the value of the secant modulus is equal to approximately

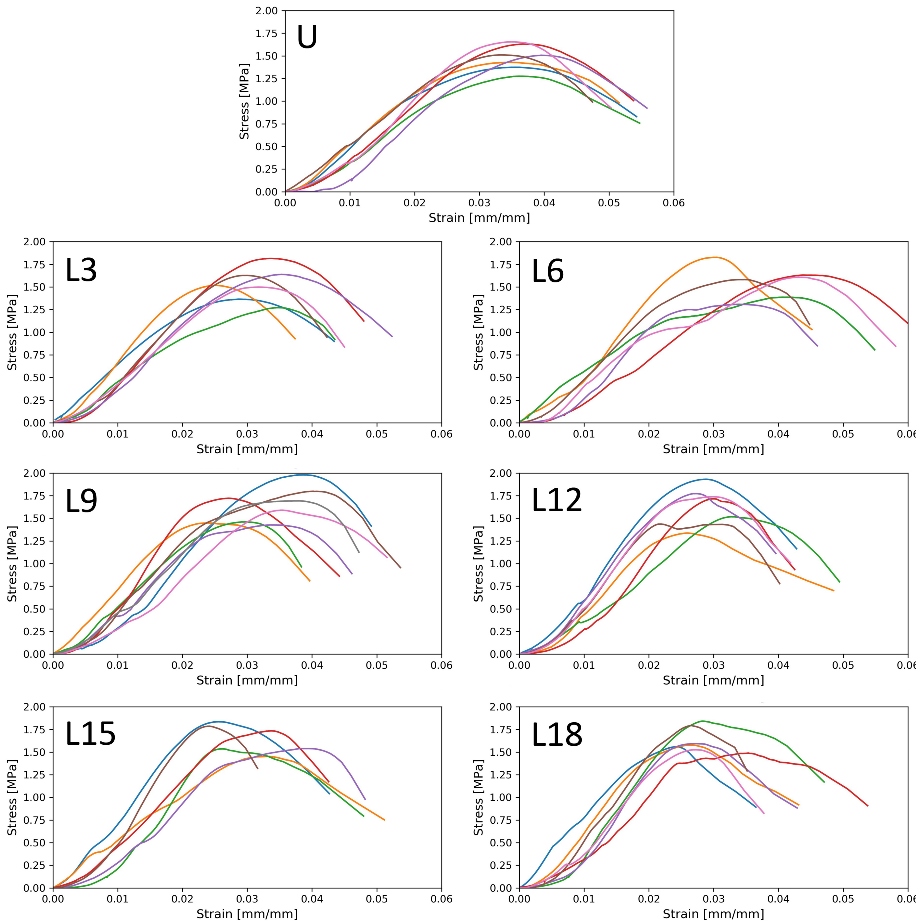

Figure 5: Stress-strain behavior of RE specimens with diverse lime contents at day 28.

0.62 times the initial tangent modulus for unstabilized, cement-stabilized and lime-stabilized rammed earth.

Table 2 shows the main results obtained from the uniaxial compressive tests for each lime content evaluated. The average coefficient of variation (CV) is equal to 11.0 % for the UCS and 17.4 % for the stiffness modulus. These values are reasonable taking into account the intrinsic heterogeneity of the material, and are comparable (and slightly lower) to the CV presented for SRE in previous studies [38, 57].

It is possible to observe that an increase in the lime content increased the UCS and E of the RE specimens and decreased the strain reached at maximum stress. The UCS at 28 days obtained for U specimens is comparable to the values commonly obtained for URE [5], and was increased by about 11 % when adding 9 % of lime, while larger lime contents did not seem to provide greater

Spec.	UCS [MPa]		E [MPa]		ε_c [mm/mm]	
U	1.48	(9.3 %)	64.97	(9.8 %)	0.036	(5.5 %)
L3	1.53	(11.9 %)	73.43	(18.0 %)	0.031	(11.8 %)
L6	1.56	(13.2 %)	72.99	(21.5 %)	0.038	(13.5 %)
L9	1.64	(11.9 %)	81.49	(16.9 %)	0.033	(17.8 %)
L12	1.64	(12.8 %)	91.01	(17.0 %)	0.028	(12.4 %)
L15	1.65	(9.6 %)	92.56	(26.5 %)	0.030	(18.9 %)
L18	1.63	(8.5 %)	93.45	(12.2 %)	0.028	(12.7 %)

Table 2: Uniaxial compressive strength (UCS), stiffness modulus (E) and strain at max. stress (ε_c) obtained for URE and LSRE specimens after 28 days of curing. Coefficient of variation in parenthesis.

strength. The reason why increasing lime contents did not improved strength is probably indicating that above that critical lime content there is an insufficient amount of aluminosilicate material in the soil to support additional stabilization reactions with the lime.

The UCS results obtained in the present study have been compared with those ones reported in literature, although the latter are very scarce and present a great dispersion. Ciancio et al. [7] obtained higher improvements (ca. 70 %) in the UCS with an optimum lime content of 4 %, but the initial strength for URE was extremely low (0.70 MPa), and so it was the maximum strength reached adding lime. Arto Torres [58] also performed compression tests on 10 cm-side cubic samples, with very high lime contents −20 and 25 %vol−, obtaining UCS equal to 2.64 MPa and 2.38 MPa, respectively. A similar dosage (18 %vol lime) was used by Canivell et al. [27], obtaining an average compressive strength of 1.87 MPa. Not very different results were obtained by Koutous and Hilali [47], leading to UCS between 1.58 MPa and 2.55 MPa for 4 %-LSRE specimens. Da Rocha et al. [26] also evaluated the UCS of LSRE, obtaining surprisingly low values (under 1.00 MPa for all lime contents from 3 to 9 %). Despite of the differences, two aspects observed in the present study were also noted by [26]: UCS increases as the lime content increases and UCS increases as the curing time increases.

The huge differences in the results showed in the diverse studies regarding lime stabilization of RE make it very difficult to draw general conclusions, so it would be necessary to carry out specific tests for particular soils and ambient conditions in order to assess the optimum lime content for the compressive strength and the maximum value of this parameter for each RE construction under consideration. If a range of UCS of LSRE should be established to have an order of magnitude, it would be from 1.00 to 2.50 MPa, a range in which the results of the present study fit.

Regarding the elastic (secant) modulus, the values obtained in the present study for the URE specimens are in agreement with those proposed by Maniatidis and Walker [59] and Bui and Morel [1]. Some other studies propose higher E values [38, 41, 60], but the enormous dispersion in the results presented in literature regarding this parameter does not allow to define a value of consensus [5, 25]. Considering the studies specifically evaluating LSRE, only Ciancio et al. [7] indicates the measurement of the stiffness, showing values between 150 MPa to 200 MPa. Again, the lack of results in literature and their variability make it very difficult to draw conclusions about this parameter.

Analyzing the variation of the stiffness when adding different lime contents, it can be observed that no relevant increases were obtained with lime contents lower than 9 %, but it significantly improved (about 25 %) when reaching that lime content. The increase in the secant stiffness modulus was even higher (over 40 %) for L12 specimens and then remained approximately constant when higher percentages of lime were added. The significance of these stiffness improvements is assessed through an ANOVA test, obtaining a p-value of 0.003, much lower than the significance level (0.05), which provides strong evidence to conclude that the population means —mean stiffness for each lime content— are significantly different. Figure 6 shows the evolution of the stiffness with the lime content, together with the variation of the compressive strength.

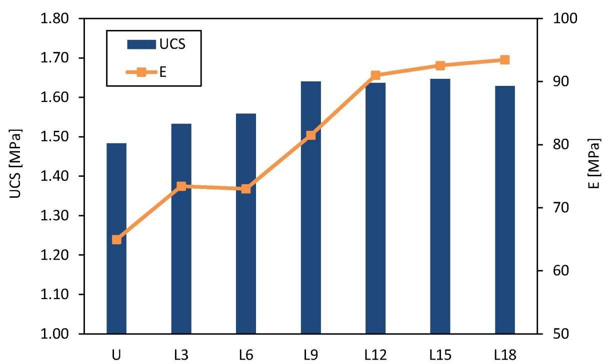

Figure 6: Average uniaxial compressive strength and stiffness for increasing lime contents at day 28 (Table 2).

In the second part of the study, UCS tests were repeated for 12 %-LSRE specimens, as it was observed that this lime content was the limit over which the improvements in the mechanical properties was almost negligible. The tests performed for the L12 specimens evaluated the strength development process for this SRE material. The results show an exponential evolution of the UCS of the specimens along time (Figure 7); Equation 2 is proposed as the expression that fits better the evolution of the UCS of the LSRE specimens over time, with a coefficient of determination $R^2 = 0.82$.

$$\mathrm{UCS} = 2.530\left(1 - \exp\left(-0.386\, t^{0.277}\right)\right) \tag{2}$$

whit UCS in MPa and the curing time, t, in days.

These results and the proposed equation indicates a maximum UCS of 2.53 MPa at infinite time. Sixty five percent of this maximum strength is developed during the first 28 days of curing, and this percentage increases to 75 %

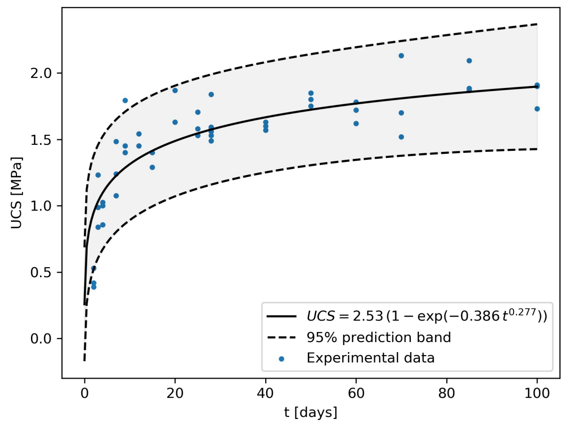

Figure 7: Development of the uniaxial compressive strength over time for L12 specimens.

if waiting until day 100. Although the UCS values obtained for 12 %-LSRE in the present study —1.64 MPa at day 28 and 1.89 MPa at day 100— are not particularly high if compared with some of the most recent results in literature that stabilize RE with diverse combinations of additives (most of them including cement), they are in agreement with most studies considering RE stabilized only or mainly with lime, as mentioned above.

Regarding the strength development process, it is common in literature to analyze the UCS of RE at relatively short periods of time (usually 28 days [7, 27, 58]), despite the fact that it is well known that the strength development of lime-stabilized earth is a long-term process [20, 22, 24]. In fact, some studies regarding LSRE [18, 26] indicate that the UCS of the material is still increasing after 100–360 days of curing. In order to reduce these long curing periods, Da Rocha et al. [26] proposed limiting the lime content and including a significant percentage of fly ash (over 25 %). There are also some examples of ancient LSRE structures constructed centuries ago that may help indicating the potential strength of this material at “infinite” time; this is the case of the Tower of Comares at the Alhambra (Granada, Spain), where cylindrical samples were extracted from its walls and tested in laboratory obtaining a compressive strength of 2.45 MPa [10, 61].

It is well known, therefore, that the strength acquisition process is slow and requires a significant amount of time to be fully developed. However, it is also possible to observe that a huge percentage of the final strength is developed during the first weeks of curing, due to the hydration reaction of lime that starts just after the lime is added to the soil in the presence of water. It was also observed that, during the first ten days of curing, the weight of the specimens significantly decreased, mainly due to the evaporation of the water present in the mixture, and then remained almost completely constant. The weight variation of the samples during their first month of curing is shown in Figure 8. A similar behavior of the moisture loss process was observed by Arto et al. [28] for LSRE specimens cured in natural ambient conditions. Curing conditions with higher relative humidity could reduce evaporation and extend the hydration process of lime, prolonging the time required for the strength to stabilized and allowing the material to reach higher strength values.

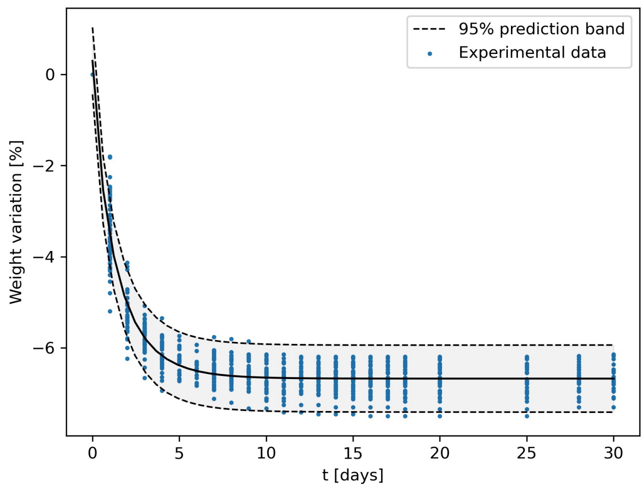

Figure 8: Weight variation of L12 specimens during the first 30 days of curing.

Evaluating the stiffness modulus, it is possible to observe the existence of a linear correlation between this parameter and the UCS of the LSRE specimens, where E is equal to ca. 57 times the UCS with $R^2 = 0.75$, as shown in Figure 9. A linear relationship between these two parameters has been noted in several previous studies regarding RE with diverse stabilizers [36, 38, 59, 62, 63]. Some relevant earth construction standards, such as NZS 4297 [64], also indicate that the stiffness can be linearly obtained from the UCS values if there is not more specific data.

4.3. Carbonation

It is also useful to evaluate the evolution of the carbonation depth in the LSRE specimens, as it is closely related to the strength development process [35]. Carbonation occurs when the lime added to the soil reacts with the CO_2 present in the air. This phenomenon should generally be avoided, as it subtracts the lime to other lime-soil reactions and hence inhibits or limits the formation of cementitious products, reducing the maximum potential strength [19, 24]. Although carbonation speed could be slowed down by limiting the CO_2 concentrations in the curing environment, this is unlikely to be possible in a real construction site, so natural ambient conditions were considered in the present study.

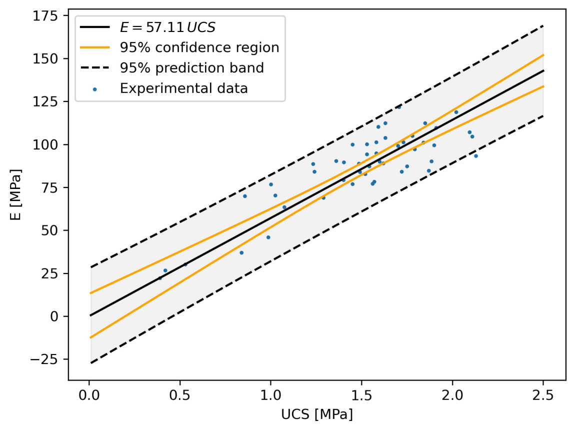

Figure 9: Stiffness modulus as a function of the uniaxial compressive strength.

The carbonation depth in the specimens was measured, after the UCS tests, as the distance between the external faces of the specimen, exposed to carbon dioxide, and the carbonation front. Van Balen and Van Gemert [65] proposed the formula $c = k\sqrt{t}$ to explain the evolution the carbonation depth (c) in lime mortars, where t is the curing time and k is an experimental factor. Basing on this expression and considering the results obtained in the present study, equation 3 is proposed to describe the evolution of the carbonation depth in the 12 %-LSRE specimens, with a coefficient of determination equal to 0.93.

$$c = 4.319\, t^{\,0.430} \tag{3}$$

where c is the carbonation depth in mm and t is the curing time in days.

Although the growth of the carbonate depth is faster during the first days of curing (Figure 10), as it happens with the strength acquisition or moisture loss, the carbonation process continues to develop for a much longer time. In the case of the 100 mm-side cubic specimens used in this study, the samples would be fully carbonated after ca. 300 days of curing. The carbonation speed also depends on the lime content, as it can be observed in Table 3, which includes the carbonation depth of the specimens for diverse lime contents at day 28, when they were subjected to the UCS tests. The carbonation depth after 28 days of curing is higher for samples with lower lime contents, probably because greater lime percentages result in a finer pore structure that impedes CO_2 permeation [17, 19, 66]. Also, as the amount of carbon dioxide in the atmosphere is controlled, a greater lime content in the material takes longer to carbonate and so a reduced carbonation rate occurs with increasing lime content.

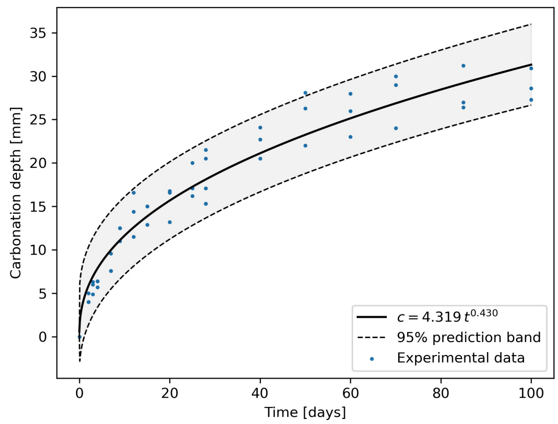

Figure 10: Evolution of the carbonation depth during the curing period.

	L3	L6	L9	L12	L15	L18
c [mm]	32	25	19	18	20	18
C.V. [%]	9.1	7.3	10.7	12.3	9.7	10.7

Table 3: Carbonation depth (c) of LSRE specimens after 28 days of curing. Mean value and coefficient of variation.

4.4. Ultrasonic pulse velocity

The UPV through the RE samples was measured before destructive UCS testing in order to assess a potential relationship between this parameter and the mechanical properties of the material. In fact, the analysis of the results shows a linear correlation between the UPV and the UCS of the LSRE specimens, following Equation 4, where UCS is expressed in MPa and UPV in km/s. This relationship and its 95 % prediction band and confidence region are shown in Figure 11.

$$\mathrm{UCS} = -1.416 + 1.897\,\mathrm{UPV} \tag{4}$$

Although there are very few studies that use the UPV technique for RE materials, some authors have already indicated the existence of a linear correlation between compressive strength and ultrasonic pulse velocity [27, 43, 67]. Therefore, and despite the evident existing dispersion in the values of the mechanical properties of RE materials, which is partially intrinsic to the heterogeneity of the material itself [5], the existing relationship between the UCS and the UPV makes the measurement of the latter a useful method to estimate the mechanical properties without damaging the sample. This can be particularly useful for existing RE structures, especially in the case of heritage buildings where destructive testing techniques cannot be applied. Previous studies have also noted

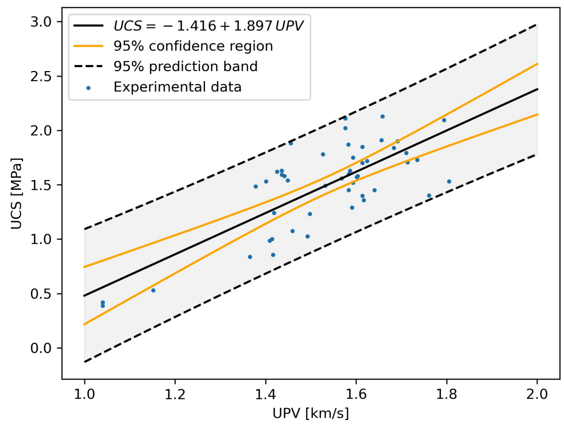

Figure 11: Uniaxial compressive strength as a function of the ultrasonic pulse velocity.

the usefulness of the UPV technique to predict the compressive behavior and to detect damage for other common construction materials, such as concrete [68, 69] or brick and stone masonry [70, 71].

For new constructions, on the other hand, UPV measurements during the curing period can be used to assess the evolution of the mechanical properties. A stabilization in the UPV values would indicate the stabilization of the UCT and stiffness, meaning that the material has already developed the majority of its strength (initial part of the strength development curve).

5. Conclusions

Rammed earth is a traditional building technique that is attracting a renewed interest due to its low environmental impact and limited construction costs. Over the last decades, the scientific research regarding RE construction has been mainly focused on unstabilized or cement-stabilized material, in addition to some other modern additives. On the other hand, very few studies have evaluated the mechanical characteristics of RE stabilized with lime, even though it is a traditional additive widely used in soil stabilization, causing an environmental impact lower than other common stabilizers such as cement, and which is present in several historic RE buildings.

In the present study, several RE samples with different lime contents and curing periods have been evaluated in order to analyze the effect of lime stabilization on the mechanical properties of the material. The results show an increase in the UCS and stiffness when increasing the lime content, in agreement with some other previous studies [7, 26], until a certain percentage of lime from which no improvement of the mechanical properties was obtained. This strength standstill is related to the lack of the aluminosilicate material in the soil, so the optimum lime content (minimum lime content for which the maximum strength is reached) may vary depending on the mineralogical characteristics of the soil, so it would be recommended to perform some UCS tests for the specific soil to be used in a construction before choosing the lime content. For the material used in the present study, representative of the soils traditionally used in RE construction in Southern Spain, the optimum lime content for the compressive strength and stiffness was equal to 12 %.

The mechanical properties of the 12 %-LSRE samples were also evaluated during 100 days of curing, observing an exponential evolution of the UCT that shows that a significant percentage of the strength is developed during the first 20–30 days, but also indicating that the strength development process could last hundreds of days (about 75 % of the predicted strength was reached by day 100). Similar behavior was observed for the material stiffness, which showed a linear relationship with the UCS, although the stiffness values showed higher dispersion, also noted in previous studies [25].

Also carbonation of the specimens, considered detrimental to strength development, was evaluated. Carbonation was observed to develop faster in samples with low lime contents, were the coarser pore structure leads to a faster carbon dioxide permeation. This phenomenon, however, occurs in a slower way than other lime-soil reactions, following a potential evolution of the form $c = a\,t^b$.

In addition, non-destructive UPV tests were performed. This technique has proved to be a useful method to estimate the mechanical properties of the material without damaging the sample, due to its linear relation with the compressive strength of the material. UPV tests could be easily performed on RE walls in a construction site, were the stabilization in the values obtained could be used as an indicator that the mechanical parameters have also increased and reached a stable value.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was supported by the Spanish Ministry of Universities via a doctoral grant to Fernando Ávila (FPU18/03607).

The study is part of the project "*Revalorización Estructural del Patrimonio Arquitectónico de Tapial en Andalucía*" (Structural Revaluation of the Rammed Earth Architectural Heritage in Andalusia), ref. A-TEP-182-UGR18, within the framework of the European Regional Development Fund Program of Andalusia 2014-2020, and has been carried out by members of the Research Group "Solid Mechanics and Structures" (TEP167) at the Sustainable Engineering Structures Laboratory (SES-Lab) of the University of Granada.

References

[1] Q. B. Bui, J. C. Morel, Assessing the anisotropy of rammed earth, Constr. Build. Mater. 23 (9) (2009) 3005–3011. doi:10.1016/j.conbuildmat.2009.04.011.

[2] J.-C. Morel, R. Charef, E. Hamard, A. Fabbri, C. Beckett, Q.-B. Bui, Earth as construction material in the circular economy context: practitioner perspectives on barriers to overcome, Philos. Trans. R. Soc. B Biol. Sci. 376 (1834) (2021) 20200182. doi:10.1098/rstb.2020.0182.

[3] S. S. D. Raavi, D. D. Tripura, Predicting and evaluating the engineering properties of unstabilized and cement stabilized fibre reinforced rammed earth blocks, Constr. Build. Mater. 262 (2020) 120845. doi:10.1016/j.conbuildmat.2020.120845.

[4] P. Walker, R. Keable, J. Martin, V. Maniatidis, Rammed earth : design and construction guidelines, 2005.

[5] F. Ávila, E. Puertas, R. Gallego, Characterization of the mechanical and physical properties of unstabilized rammed earth: A review, Constr. Build. Mater. 270 (2021) 121435. doi:10.1016/j.conbuildmat.2020.121435.

[6] D. Alex, Recognition of a heritage in danger: Rammed-earth architecture in Lyon city, France, IOP Conf. Ser. Earth Environ. Sci. 143 (1) (2018). doi:10.1088/1755-1315/143/1/012054.

[7] D. Ciancio, C. T. S. Beckett, J. A. H. Carraro, Optimum lime content identification for lime-stabilised rammed earth, Constr. Build. Mater. 53 (2014) 59–65. doi:10.1016/j.conbuildmat.2013.11.077.

[8] R. El Nabouch, Q. B. Bui, O. Plé, P. Perrotin, Assessing the in-plane seismic performance of rammed earth walls by using horizontal loading tests, Eng. Struct. 145 (2017) 153–161. doi:10.1016/j.engstruct.2017.05.027.

[9] N. Gamrani, K. R'kha Chaham, M. Ibnoussina, F. Fratini, L. Rovero, U. Tonietti, M. Mansori, L. Daoudi, C. Favotto, N. Youbi, The particular "rammed earth" of the Saadian sugar refinery of Chichaoua (XVIth century, Morocco): Mineralogical, chemical and mechanical characteristics, Environ. Earth Sci. 66 (2012) 129–140. doi:10.1007/s12665-011-1214-6.

[10] T. González Limón, M. Álvarez de Buergo, A. de las Casas Gómez, Estudio de los materiales y de las fábricas de la Torre de Comares de la Alhambra, Cuad. la Alhambra 33-34 (1997) 95–104.

[11] D. Gandreau, L. Delboy, CRATerre-ENSAG (France), UNESCO World heritage inventory of earthen architecture, 2012.
URL https://unesdoc.unesco.org/ark:/48223/pf0000217020

[12] J. Martínez, F. Ávila, E. Puertas, A. Burgos, R. Gallego, Historical and architectural study for the numerical modeling of heritage buildings: the Tower of Comares of the Alhambra (Granada, Spain), Inf. la Construcción 74 (565) (2022) e429. doi:10.3989/ic.86683.

[13] I. Valverde-Espinosa, E. Ontiveros-Ortega, E. Sebastián-Pardo, El tapial de las murallas de Granada, Re. Rev. Edif. 26 (1997) 58–63.
URL https://revistas.unav.edu/index.php/revista-de-edificacion/article/view/34878/30040

[14] J. J. Martín-del Rio, J. Canivell, M. Torres-González, E. J. Mascort-Albea, R. Romero-Hernández, J. M. Alducin-Ochoa, F. J. Alejandre-Sánchez, Analysis of the materials and state of conservation of the medieval rammed earth walls of Seville (Spain), J. Build. Eng. 44 (2021) 103381. doi:10.1016/j.jobe.2021.103381.

[15] M. I. Gomes, T. D. Gonçalves, P. Faria, Hydric Behavior of Earth Materials and the Effects of Their Stabilization with Cement or Lime: Study on Repair Mortars for Historical Rammed Earth Structures, J. Mater. Civ. Eng. 28 (7) (2016) 04016041. doi:10.1061/(asce)mt.1943-5533.0001536.

[16] E. Ontiveros Ortega, E. Sebastián Pardo, I. Valverde Espinosa, F. J. Gallego Roca, Estudio de los materiales de construcción de las murallas del Albayzín (Granada), PH Boletín del Inst. Andaluz del Patrim. Histórico 66 (2008) 32–47.
URL http://hdl.handle.net/11532/245294

[17] Y. Luo, H. Zhong, F. Bao, Z. Guo, P. Ni, Insights into natural and carbonation curing of ancient Chinese rammed earth mixed with brown sugar, Constr. Build. Mater. 317 (2022) 125969. doi:10.1016/j.conbuildmat.2021.125969.

[18] J. d. J. Arrieta Baldovino, R. L. dos Santos Izzo, E. Batista Moreira, J. Lundgren Rose, Optimizing the evolution of strength for lime-stabilized rammed soil, J. Rock Mech. Geotech. Eng. 11 (2019) 882–891. doi:10.1016/j.jrmge.2018.10.008.

[19] F. G. Bell, Lime stabilization of clay minerals and soils, Eng. Geol. 42 (4) (1996) 223–237. doi:10.1016/0013-7952(96)00028-2.

[20] J. B. Croft, The structures of soils stabilized with cementitious agents, Eng. Geol. 2 (2) (1967) 63–80. doi:10.1016/0013-7952(67)90025-7.

[21] G. Deep, Influence of lime and chicken mesh on compaction behaviour and strength properties of soil, Mater. Today Proc. (2020). doi:10.1016/j.matpr.2020.08.663.

[22] S. Islam, N. M. Hoque, M. A. Hoque, P. N. Mishra, M. M. Mamun, S. Dey, Strength development in fine-grained paddy field soil by lime addition, J. Build. Eng. 26 (2019) 100857. doi:10.1016/j.jobe.2019.100857.

[23] O. Cuisinier, D. Deneele, F. Masrouri, Shear strength behaviour of compacted clayey soils percolated with an alkaline solution, Eng. Geol. 108 (3-4) (2009) 177–188. doi:10.1016/j.enggeo.2009.07.012.

[24] A. K. Jha, P. V. Sivapullaiah, Lime Stabilization of Soil: A Physico-Chemical and Micro-Mechanistic Perspective, Indian Geotech. J. 50 (3) (2020) 339–347. doi:10.1007/s40098-019-00371-9.
URL https://doi.org/10.1007/s40098-019-00371-9

[25] F. Ávila, E. Puertas, R. Gallego, Characterization of the mechanical and physical properties of stabilized rammed earth: A review, Constr. Build. Mater. 325 (2022) 126693. doi:10.1016/j.conbuildmat.2022.126693.

[26] C. G. Da Rocha, N. C. Consoli, A. Dalla Rosa Johann, Greening stabilized rammed earth: Devising more sustainable dosages based on strength controlling equations, J. Clean. Prod. 66 (2014) 19–26. doi:10.1016/j.jclepro.2013.11.041.

[27] J. Canivell, J. J. Martin-del Rio, F. J. Alejandre, J. García-Heras, A. Jimenez-Aguilar, Considerations on the physical and mechanical properties of lime-stabilized rammed earth walls and their evaluation by ultrasonic pulse velocity testing, Constr. Build. Mater. 191 (2018) 826–836. doi:10.1016/j.conbuildmat.2018.09.207.

[28] I. Arto, R. Gallego, H. Cifuentes, E. Puertas, M. L. Gutiérrez-Carrillo, Fracture behavior of rammed earth in historic buildings, Constr. Build. Mater. 289 (2021) 123167. doi:10.1016/j.conbuildmat.2021.123167.

[29] S.-H. Kang, Y.-H. Kwon, J. Moon, Quantitative analysis of CO2 uptake and mechanical properties of air lime-based materials, Energies 12 (2019) 2093. doi:10.3390/en12152903.

[30] CEMBUREAU, The role of cement in the 2050 low carbon economy, Tech. rep. (2013). URL https://cembureau.eu/media/cpvoin5t/cembureau_2050roadmap_lowcarboneconomy_2013-09-01.pdf

[31] Portland Cement Association, Carbon footprint, Think harder. Concr. URL https://www.cement.org/docs/default-source/th-paving-pdfs/sustainability/carbon-foot-print.pdf

[32] V. Toufigh, P. Ghassemi, M. Azizmohammadi, M. Ghaemian, H. Rajabi, P. Ghassemi, Mechanical properties and environmental impact of rubberized fly ash- and red mud-based geopolymer concrete, Eur. J. Environ. Civ. Eng. (2022). doi:10.1080/19648189.2021.2018358.

[33] Y. Shan, Z. Liu, D. Guan, CO2 emissions from China's lime industry, Appl. Energy 166 (2016) 245–252. doi:10.1016/j.apenergy.2015.04.091.

[34] A. J. Edwards, Properties of Hydraulic and Non-Hydraulic Limes for Use in Construction, Ph.d. thesis, Napier University (2005). URL https://www.napier.ac.uk/$\sim$/media/worktribe/output-252838/edwardspdf.pdf

[35] A. El-Turki, R. J. Ball, G. C. Allen, Carbonation of natural hydraulic lime (NHL) 3.5, in: R. K. Dhir, T. A. Harrison, M. D. Newlands (Eds.), Cem. Comb. Durable Concr., Thomas Telford Ltd., Dundee, UK, 2005, pp. 300–308.

[36] M. Kosarimovahhed, V. Toufigh, Sustainable usage of waste materials as stabilizer in rammed earth structures, J. Clean. Prod. 277 (2020) 123279. doi:10.1016/j.jclepro.2020.123279.

[37] S. Raj, A. K. Sharma, K. B. Anand, Performance appraisal of coal ash stabilized rammed earth, J. Build. Eng. 18 (2018) 51–57. doi:10.1016/j.jobe.2018.03.001.

[38] V. Toufigh, E. Kianfar, The effects of stabilizers on the thermal and the mechanical properties of rammed earth at various humidities and their environmental impacts, Constr. Build. Mater. 200 (2019) 616–629. doi:10.1016/j.conbuildmat.2018.12.050.

[39] H. Houben, H. Guillaud, CRAterre, Intermediate Technology Publications, Earth construction: a comprehensive guide, Intermediate Technology Publications, London, UK, 1994.

[40] F. J. Alejandre, J. J. Martín del Río, Caracterización analítica de la muralla tapial almohade de San Juan de Aznalfarache, in: AHTER-CRIATiC (Ed.), Construir con tierra ayer y hoy, V Semin. Iberoam. Construcción con tierra, Mendoza, Argentina, 2006, p. 119. URL https://www.researchgate.net/publication/266014199

[41] R. El Nabouch, Mechanical behavior of rammed earth walls under Pushover tests, Ph.d. thesis, Université Grenoble Alpes (2017). URL https://tel.archives-ouvertes.fr/tel-01707009/document

[42] M. Hall, Y. Djerbib, Rammed earth sample production: Context, recommendations and consistency, Constr. Build. Mater. 18 (4) (2004) 281–286. doi:10.1016/j.conbuildmat.2003.11.001.

[43] J. J. Martín-del Rio, J. Canivell, R. M. Falcón, The use of non-destructive testing to evaluate the compressive strength of a lime-stabilised rammed-earth wall: Rebound index and ultrasonic pulse velocity, Constr. Build. Mater. 242 (2020) 118060 Contents. doi:10.1016/j.conbuildmat.2020.118060.

[44] D. D. Tripura, K. D. Singh, Characteristic properties of cement-stabilized rammed earth blocks, J. Mater. Civ. Eng. 27 (7) (2015) 04014214. doi:10.1061/(ASCE)MT.1943-5533.0001170.

[45] AENOR, UNE 103501:1994 Geotecnia. Ensayo de compactación. Proctor modificado. (1994).

[46] M. M. Hallal, S. Sadek, S. S. Najjar, Evaluation of engineering characteristics of stabilized rammed-earth material sourced from natural fines-rich soil, J. Mater. Civ. Eng. 30 (11) (2018) 04018273. doi:10.1061/(ASCE)MT.1943-5533.0002481.

[47] A. Koutous, E. Hilali, Reinforcing rammed earth with plant fibers: A case study, Case Stud. Constr. Mater. 14 (February) (2021) e00514. doi:10.1016/j.cscm.2021.e00514.

[48] New Zealand Standard, NZS 4298:1998. Materials and workmanship for earth buildings (1998).
URL https://www.standards.govt.nz/sponsored-standards/building-standards/nzs4298/

[49] CEN, EN 12390-3. Testing hardening concrete. Part 3: Compressive strength of test specimens (2020).

[50] CEN, EN 12390-12. Testing hardened concrete. Part 12: Determination of the carbonation resistance of concrete. Accelerated carbonation method. (2020).

[51] S. Kashif Ur Rehman, Z. Ibrahim, S. A. Memon, M. Jameel, Nondestructive test methods for concrete bridges: A review, Constr. Build. Mater. 107 (2016) 58–86. doi:10.1016/j.conbuildmat.2015.12.011.

[52] AENOR. CTN 83 - Hormigón, UNE-EN 12390-3. Ensayos de hormigón endurecido. Parte 3: Determinación de la resistencia a compresión de probetas (2020).

[53] C. T. Beckett, M. R. Hall, C. E. Augarde, Macrostructural changes in compacted earthen construction materials under loading, Acta Geotech. 8 (2013) 423–438. doi:10.1007/s11440-012-0203-6.

[54] H. Fardoun, J. Saliba, N. Saiyouri, Evolution of acoustic emission activity throughout fine recycled aggregate earth concrete under compressive tests, Theor. Appl. Fract. Mech. 119 (2022) 103365. doi:10.1016/j.tafmec.2022.103365.

[55] L. Miccoli, D. V. Oliveira, R. A. Silva, U. Müller, L. Schueremans, Static behaviour of rammed earth: experimental testing and finite element modelling, Mater. Struct. Constr. 48 (10) (2015) 3443–3456. doi:10.1617/s11527-014-0411-7.

[56] ASTM, C469/C469M Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (2014). doi:10.1520/C0469.

[57] E. Kianfar, V. Toufigh, Reliability analysis of rammed earth structures, Constr. Build. Mater. 127 (2016) 884–895. doi:10.1016/j.conbuildmat.2016.10.052.

[58] I. Arto Torres, Caracterización mecánica del tapial y su aplicación a estructuras existentes mediante el uso de ensayos no destructivos, Ph.d. thesis, University of Granada (2021).
URL http://hdl.handle.net/10481/69859

[59] V. Maniatidis, P. Walker, Structural Capacity of Rammed Earth in Compression, J. Mater. Civ. Eng. 20 (3) (2008) 230–238. doi:10.1061/(ASCE)0899-1561(2008)20.

[60] T. T. Bui, Q. B. Bui, A. Limam, S. Maximilien, Failure of rammed earth walls: From observations to quantifications, Constr. Build. Mater. 51 (2014) 295–302. doi:10.1016/j.conbuildmat.2013.10.053.

[61] A. Santos, V. Cuéllar, J. M. Martinez, L. Salinas, Ground-structure interaction analysis of the Tower of Comarès, Alhambra of Granada, Spain, in: 14th Int. Conf. Soil Mech. Found. Eng., ISSMGE, Hamburg, Germany, 1997, pp. 1025–1028.
URL https://www.issmge.org/uploads/publications/1/31/1997_02_0065.pdf

[62] V. Strazzeri, A. Karrech, M. Elchalakani, Micromechanics modelling of cement stabilised rammed earth, Mech. Mater. 148 (March) (2020) 103540. doi:10.1016/j.mechmat.2020.103540.
URL https://doi.org/10.1016/j.mechmat.2020.103540

[63] P. Zare, S. Sheikhi Narani, M. Abbaspour, A. Fahimifar, S. M. Mir Mohammad Hosseini, P. Zare, Experimental investigation of non-stabilized and cement-stabilized rammed earth reinforcement by Waste Tire Textile Fibers (WTTFs), Constr. Build. Mater. 260 (2020) 120432. doi:10.1016/j.conbuildmat.2020.120432.

[64] New Zealand Standard, NZS 4297:1998. Engineering design of earth buildings (1998).
URL https://www.standards.govt.nz/sponsored-standards/building-standards/nzs4297/

[65] K. Van Balen, D. Van Gemert, Modelling lime mortar carbonation, Mater. Struct. 27 (7) (1994) 393–398. doi:10.1007/BF02473442.

[66] A. Idder, A. Hamouine, B. Labbaci, R. Abdeldjebar, The porosity of stabilized earth blocks with the addition plant fibers of the date palm, Civ. Eng. J. 6 (3) (2020) 478–494. doi:10.28991/cej-2020-03091485.

[67] A. Khan, R. Gupta, M. Garg, Determining material characteristics of “Rammed Earth” using Non-Destructive Test methods for structural design, Structures 20 (May) (2019) 399–410. doi:10.1016/j.istruc.2019.05.003.

[68] P. Ghassemi, H. Rajabi, V. Toufigh, Fatigue performance of polymer and ordinary cement concrete under corrosive conditions: A comparative study, Eng. Fail. Anal. 111 (2020) 104493. doi:10.1016/j.engfailanal.2020.104493.

[69] P. Ghassemi, V. Toufigh, Durability of epoxy polymer and ordinary cement concrete in aggressive environments, Constr. Build. Mater. 234 (2020) 117887. doi:10.1016/j.conbuildmat.2019.117887.

[70] N. Makoond, L. Pelà, C. Molins, Dynamic elastic properties of brick masonry constituents, Constr. Build. Mater. 199 (2019) 756–770. doi:10.1016/j.conbuildmat.2018.12.071.

[71] E. Vasanelli, D. Colangiuli, A. Calia, Z. M. Sbartaï, D. Breysse, Combining non-invasive techniques for reliable prediction of soft stone strength in historic masonries, Constr. Build. Mater. 146 (2017) 744–754. doi:10.1016/j.conbuildmat.2017.04.146.