Considerations on the physical and mechanical properties of lime-stabilized rammed earth walls and their evaluation by ultrasonic pulse velocity testing

Abstract *(max. 100 words)*

This study examines the influence of mixing moisture content on the compressive strength, density and porosity of a rammed earth wall, using ultrasound as a complementary technique. Non-parametric and multivariate statistical techniques were applied to analyze the behaviour of variables with a sufficiently large population. The statistical analysis demonstrated that excessive or insufficient mixing moisture content directly determines the physical-mechanical properties of such walls. Ultrasound was confirmed as a valid technique for assessing the quality of a wall, since its response, albeit with certain limitations, was consistent with physical-mechanical properties.

Highlights

- The influence of mixing moisture content on physical-mechanical properties was studied.
- Ultrasound was used as a complementary technique to assess quality.
- Non-parametric and multivariate statistical techniques were applied.
- The mixing moisture content has a decisive influence on physical-mechanical properties.
- Ultrasound can be used to qualitatively assess the quality of a rammed-earth wall.

Keywords *(max. 10 key words)*

Rammed earth, ultrasonic test, compressive strength, porosity, dry density, non-destructive testing.

1. Introduction

The study of the mechanical properties of rammed earth currently presents many gaps in relation to aspects associated with standardization, test methodology and relationships with other properties of this material. As far as standardization is concerned, although some countries have researched this subject in greater depth, there is still a need to develop the control of execution techniques and experimental tests to determine the quality of rammed earth, thus continuing to prevent the potential of this sustainable technique to be fully exploited. In terms of the test methodologies, existing research focuses on studies of the mechanical strength of unstabilized rammed-earth walls or stabilized mainly with cement, such as the studies carried out by Jayasinghe and Kamaladasa [1], Kamaladasa and Jayasinghe [2], Ciancio and Gibbings [3] or Ciancio et al. [4], and only a few researchers have considered stabilization with lime, for example Ciancio et al. [4] or Da Rocha et al. [5], although this material is often used in the conservation of heritage buildings, since walls made with these materials are more compatible with existing support materials.

One of the most influential factors on the mechanical strength of rammed earth walls is mixing moisture content (MC), which has been taken into account to determine the optimum moisture content (OM) of compaction, and is often determined by the normal [6] or modified Proctor compaction test. However, until now consideration has been given mainly to the moisture content of rammed earth at the time of testing, which has been associated with the suction effect for unstabilized rammed earth walls [7,8], or with mechanical compressive strength [8,9]. Therefore, although MC directly affects density and porosity in stabilized soils [8], it has not been considered as a variable to analyze the quality or strength of a rammed earth wall. It is also necessary to highlight the difficulty in maintaining MC constant between different batches, either on site or in the laboratory, since this will depends on the mixing method used, soil composition or the presence of lime, among other factors, causing these variations to alter certain physical-mechanical characteristics of rammed earth structures.

To find studies of the application of non-destructive tests on walls, it was necessary to review research carried out on historic buildings, in which attempts have been made to correlate the results obtained using a sclerometer with wall unconfined compressive strength [10], or those carried out by Liang [11] using ultrasound, in order to obtain a better understanding of the thermo-mechanical and ageing responses of buildings under thermal loads and affected by earthquakes. Galán-Marín et al. [12] used ultrasound to evaluate the retraction and adhesion of fibres in blocks of earth and suggest that this technique could be used to evaluate mechanical characteristics. Mansour et al. [13] propose the use of low frequency waves to study certain physical properties of compressed earth blocks, with interesting results. Except for the recent study by Bernat-Maso et al. [14], who propose ultrasound to assess moisture content and determine Young's modulus, no studies have faithfully correlated the results of these types of non-destructive tests with the mechanical properties of rammed earth walls, and much less so during their execution, in contrast to the situation for other types of materials such as concrete [15], mortar, etc. Furthermore, many studies do not statistically process the results to verify their reliability, either because only a small number of samples [1,8,18-20] or because they decided to perform a descriptive analysis of the results [3,4,21-23].

The objective of this research was to analyze the influence of MC on a rammed earth wall with a specific dosage and pre-established compaction energy on physical-mechanical properties (density, porosity and compressive strength) using ultrasonic pulse velocity as a complementary support technique.

2. Material and methods

This study was carried out within the context of a research project[1] on the restoration of the Alcázar (Fortress) of King Pedro in Carmona (Seville). The construction materials used in restoration work therefore served as a reference to establish the basis of the analysis. The rammed earth used in this research consisted of a mixture of sand, calcareous soil (a biocalcarenite known locally as "albero"), sub-soil from the surrounding area and hydraulic lime HL5. The dosage in volume (5 sub-soil: 2 sand: 2 water: 2 lime) was the same as that used and corresponded approximately to a ratio of sand, gravel and silty clay of 5:4:1, according to the coding system proposed by Hall [16].

Soil suitability was studied and assessed by means of on-site tests [23] (drop test, ribbon test, visual inspection, sedimentation) and laboratory tests: particle size distribution [24], plasticity limits [25,26], X-ray powder diffraction (XRD) proposed for determining overall mineralogy, organic matter content [27,28] and optimum water content [6].

Since no Spanish standard regulating the elaboration of rammed earth (RE) specimens is available, a procedure was developed in accordance with recommendations provided in international standards and manuals [29,30] and involving RE cube samples [16], although cylindrical shapes have been considered by other authors [4] or the UNE-EN concrete standard [31]. In order to obtain statistically representative results, 40 cube samples were gathered in 5 batches of 8 samples. Each batch comprised 4 moulds measuring 10x10x40 cm (Fig. 1). First, four (4) prismatic samples per batch measuring 30 cm in height were compacted. After 28-days' curing in laboratory conditions (temperatures of 18-22°C and 50-60% relative humidity), they

[1]Project 68/83-2738 - Analysis of materials for the restoration of a rammed earth wall at the Alcazar (Fortess) of King Pedro, Camona, Seville. University of Seville.

were cut into two identical sections and then cut again into two pieces, leaving 2 cubes measuring 10 cm on each side and two 5 cm-tall slices for each prismatic mould. According to the UNE-EN 12504-1 standard [31], the size of a cube specimen must comply with the ratio of 1:3 between the maximum aggregate size and the test specimen edge. Consequently, particles larger than 3.15 cm were discarded.

Samples were identified by a code according to the batch number (from 1 to 5), and their corresponding 8 cube specimens, as represented in Figure 1, i.e. sample 1.1 was the first cube specimen in the first batch.

In order to ensure the best match between the samples and real conditions, RE components were mixed in a steel drum concrete mixer and samples were compacted through manual ramming. The moisture content of each batch was checked in accordance with the UNE-EN-ISO-17892-1 standard [32] to establish several mixing moisture steps. OM and maximum dry density were determined by the Proctor compaction method [6]. MC was intended to range below OM since once OM was exceeded, proper compaction was difficult to achieve due to the high water content and the plasticity of the mix. The MC of each batch was established as the average of 4 samples and determined in accordance with the UNE 103-300:93 standard [33]. As it was necessary to establish mixture moisture ranges, we started with the known dry moisture of the earth. Water was then added as a percentage of weight until the moisture established for each batch was achieved. To conserve initial soil moisture content, each batch was kept insulated inside a plastic bag before being mixed.

Since manual ramming was employed, the Proctor compaction method was followed in order to establish the amount of compaction energy needed to ensure maximum density, as proposed by Ciancio and Gibbings [3] and Ciancio, Jaquin and Walker [4]. To that end, compaction energy per volume was controlled by the weight of the rammer (3.3 kg), in addition to the number of strokes and the free fall height of the rammer. The compaction energy per volume for manual ramming must correspond to the Proctor test. In order to achieve the same MC for the specimens, they were cured for 28 days in the same environmental conditions, as proposed by Ciancio, Jaquin, and Walker [4], Hall and Djerbid [16], and as stated by Standard New Zealand [29], and mortar regulation UNE-EN 1015-11:2000 [34].

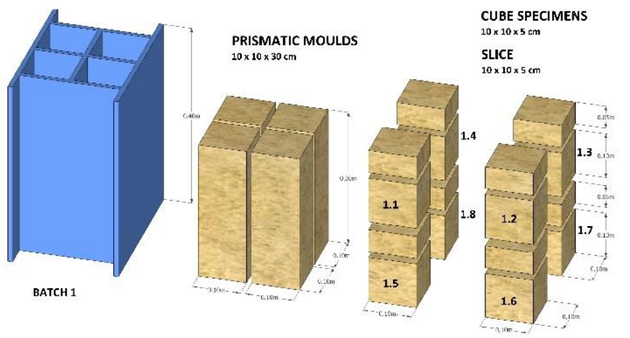


Fig. 1. Preparation of samples from prismatic shape moulds.

Once cured, open porosity and dry density were obtained for the 5 cm-tall slices by means of a water saturation method in a vacuum. To that end dry, saturated and hydrostatic weights were established as provided in UNE-EN-1936 [35]. Ultrasonic tests were performed on 40 cube samples with a Ultrasonic-Tester BP-7 Series (UltraTest Gmbh), following the procedures established in the UNE-EN 12504-4 standard [36]. Three readings were recorded for each orientation so that each specimen was represented by three average measurements of ultrasonic pulse velocity (UPV), namely X-UPV, Y-UPV, and Z-UPV (Fig. 2), corresponding to the orientation of compaction. Due to the roughness of surfaces, modelling clay was used as a coupling for sensors.

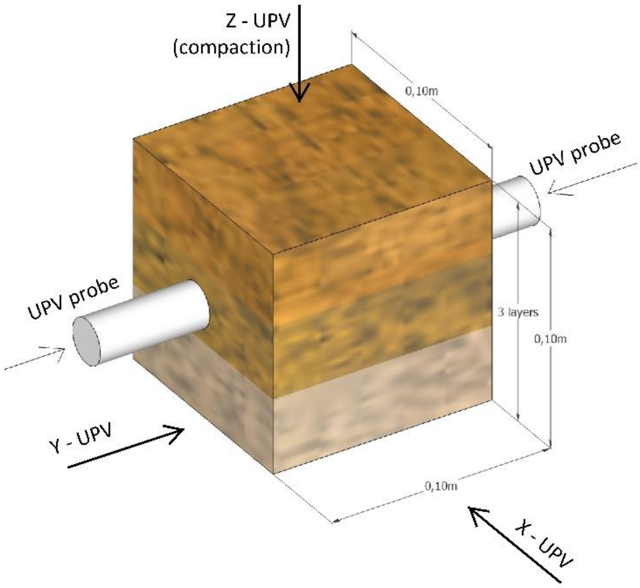


Fig. 2. Cube specimen of RE and orientations of the ultrasonic pulse test.

Unconfined compressive strength (CS) was determined at 28 days ageing using an electromechanical strength testing machine (TCCSL model PCI-30t) equipped with a 30-t load cell, with a loading rate of 330 N/s and breaking times of 30–90 s, following the procedure described in the UNE-EN 1015-11 standard [34]. This value corresponds to the interval established for mortars at 5 N/s to 500 N/s and also proposed by Hall and Djerbib [16]. The same 40 specimens tested to determine UPV were capped with sulphur and tested in the orthogonal orientation of compaction layers in order to determine CS.

3. Results

3.1 Results on raw materials (particle size distribution, Proctor, limits)

Sub-soil and complete dosage employed (5 soil: 2 sand: 2 "albero": 2 lime) was analysed in terms of particle size distribution (PSD) and is shown in Figure 3. The upper and lower limits corresponded to Hall and Djerbib [16] and should be taken as an approximate guide, since RE margins are usually rather wide. Nevertheless, the subsoil curve showed a certain deficiency in sand (0.5 to 0.25 mm), which was corrected in the complete dosage although the silt-clay ratio

(>0.063 mm) decreased to below the recommended limit. Fine particles are essential to provide mechanical strength in non-stabilized RE where water suction has been discussed as a source of cohesion [7]. However when dealing with lime-stabilized RE, strength is provided by the increase in density, enhancing particle interlocking and lime bonding.

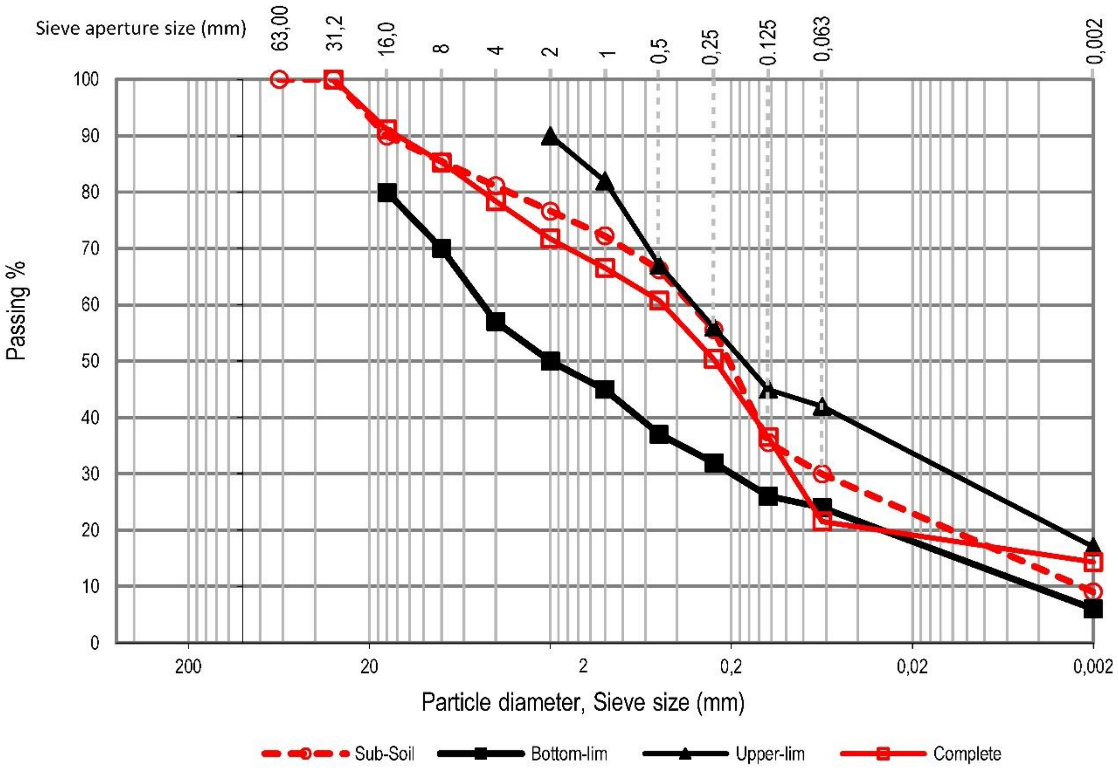


Fig. 3. Particle grading curves for sub-soil and complete dosage.

OM was established for the complete dosage in accordance with the UNE 103-500 standard [6] and is shown in Figure 4. OM is 18.25%, corresponding to a dry density of 1.63 g/cm^3. These values served as a reference to be followed during sample production. The 40 cube specimens were produced in several intervals, 5 batches for each group of 8 specimens were prepared and mixture moisture content was controlled to ensure it remained within the dry mixture-to-OM range, without exceeding OM.

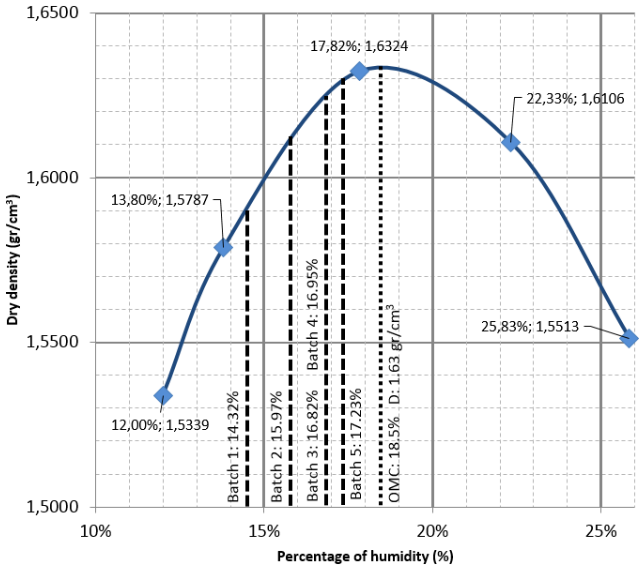


Fig. 4. OM for the complete dosage and MC for all the batches.

3.2 Moisture content (MC) of the batches.

The mixture moisture content of the batches are shown in Table 1. The data were ordered according to increasing moisture content (MC1 to MC5) up to values close to OM. It was not possible to take moisture values above OM since the soil quickly became plastic and this made it difficult to execute the specimens.

Table 1. Moulding moisture content (MC) for all the batches.

3.3 Physical-mechanical properties (density, porosity and strength)

Porosity and dry density are opposite parameters also related to the mechanical performance of stabilized RE as stated [37]. As expected, the lower the dry density, the higher the porosity (Table 2). In relation to OM, a maximum dry density of 1.63 g/cm^3 corresponds to a mean open porosity of 38%. The porosity values were therefore approximately the same as others for lime-stabilized RE [37] and corresponded to not very dense material with a considerable volume of pores in comparison to more dense materials.

The CS values for the 40 specimens are shown in Table 2. All samples complied with the recommended CS as established in the NZS 4298 standard [29] and in Standards Australia [38]. Samples corresponding to MC1 (14.32%) showed the lowest CS values, which corresponded to the lowest measured percentage of water added during mixing. In fact, these samples had the highest porosity ratios, so given the same compaction energy applied, these soils did not reach similar densities.

Table 2. Dry density, porosity and CS of the specimens and UPV for the RE specimens. X-UPV, Y-UPV, Z-UPV: UPV in X, Y and Z orientations.

3.4 Ultrasonic pulse velocity

After curing for 28 days, the 40 cube specimens were tested with the ultrasonic pulse device, as described for the method. Each sample was measured before testing the ultrasonic pulse velocity in order to determine its height, length and width (in cm) and thus establish the UPV (cm/μs) for each orientation. UPV is represented in Table 2 for each orientation, with orientation Z corresponding to the direction of compaction. Table 2 presents the results for the 40 specimens, grouped into 8 samples, corresponding to each of the 5 batches.

3.5 Statistical analysis

Initially CS was to be represented according to the other variables (X-UPV, Y-UPV, Z-UPV, D, P) by means of a scattered chart in order to analyze their distribution. Figure 5 shows the groups of individuals presented according to batch moisture content (MC1 to MC5), suggesting that batch moisture content may have influenced the other variables.

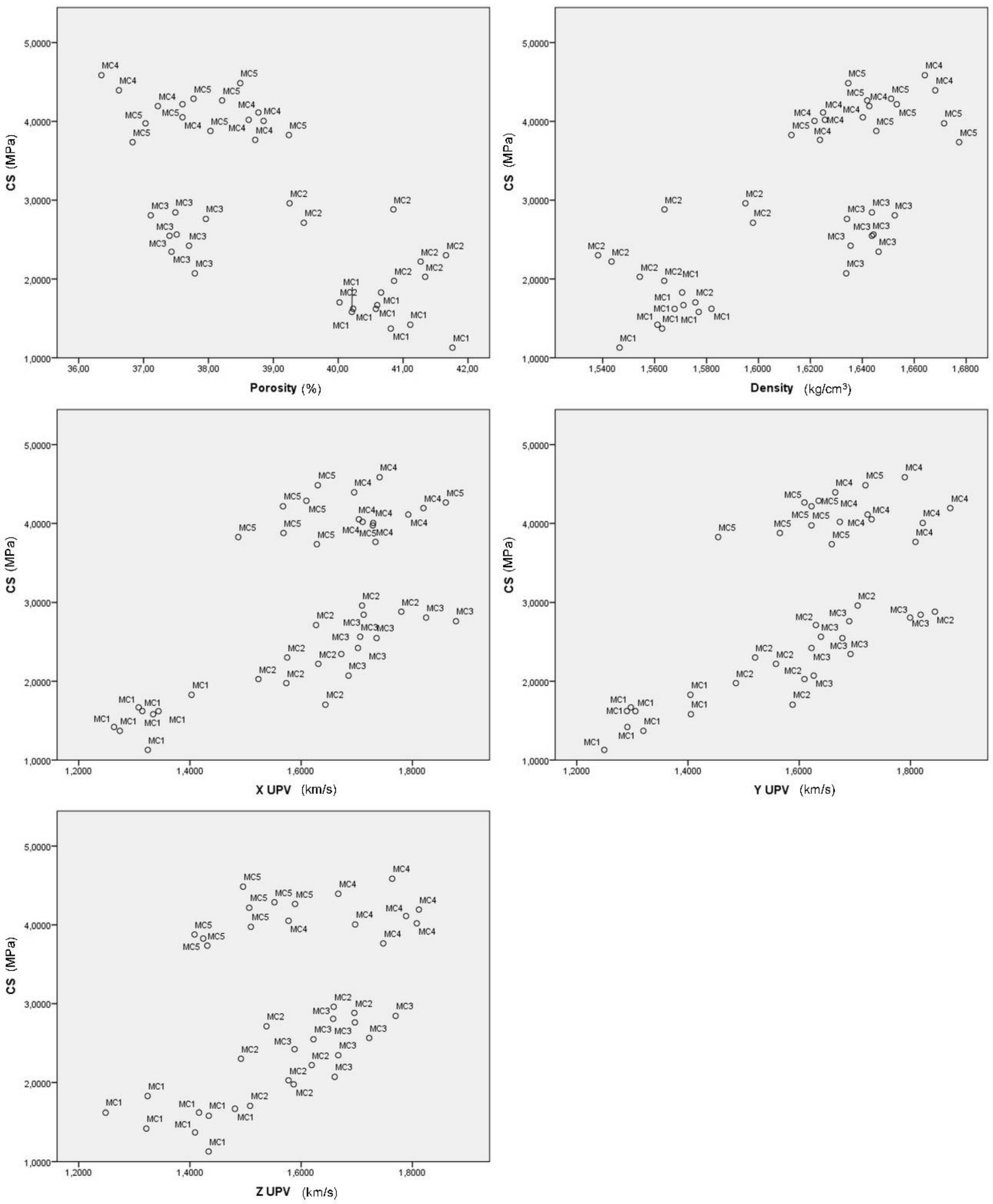
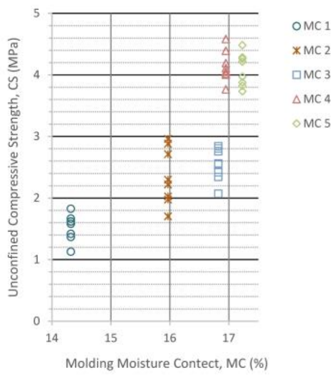


Fig. 5. Representation of CS according to the variables X-UPV, Y-UPV, Z-UPV, D, P.

Given the suspicion that the behaviour of these variables may have differed depending on the MC and since the number of individuals per batch was small (8 specimens), the Kruskal-Wallis non-parametric technique was chosen to analyze whether the behaviour of each variable was the same for each MC. The result obtained using this technique yielded a value of p-value = 0 in each of the studies (CS, UPV, D, P), allowing us to affirm that each variable behaved differently from a mathematical standpoint depending on the MC in each case. Therefore, the decision was taken to determine whether subgroups could be established according to moisture content for each variable. For this purpose, a multiple comparisons technique was applied. Table 3 shows the homogeneous subgroups that were formed for density, porosity and CS, which also corresponded to groups that maintained similar mixture moisture levels. The groupings for density and porosity were the same, with the lowest moisture levels (MC1, MC2) grouped in a separate subgroup from the higher moisture levels (MC3, MC4, MC5). Although the situation with CS was similar with respect to the order of moisture levels, 3 homogeneous subgroups were proposed (MC1, MC2-3, MC4-5), corresponding to the groupings shown in the diagrams in Fig. 6 for CS and MC.



	Subset according to CS		
Molding moisture content (MC)	1	2	3
MC1	4.625		
MC2		15.250	
MC3		17.625	
MC5			32.000
MC4			33.000
Test statistic	--	0.893	0.176
Significance (test side 2)	--	0.345	0.674
Adjusted sign. (test side 2)	--	0.652	0.940
Homogeneous subset are based on asymptotic significances. The significance level is 0.05.			
Each value for MC1-5 corresponds to the average range of CS.			

Fig. 6. Right: Homogeneous subsets based on unconfined compressive strength (CS). Left: CS is plotted according to each the MC of each batch.

The subgroups established for UPV differed somewhat although the extreme subsets always coincided with lowest moisture content (MC1) and with one of the higher moisture contents (MC4). Therefore, it may be stated that mixture moisture content had a decisive influence on the physical properties of the wall and that the homogeneous groupings corresponded to two sets: high MC and low MC.

Table 3. Homogeneous subsets based on density and porosity

Finally, all the properties were analysed together, without considering moisture, applying the multivariate Cluster-Analysis technique (k-means clustering method) applied to two groups. The aim was to define groups of specimens that formed clusters with a high degree of internal homogeneity. With the exception of one specimen (no. 8, batch 1), all the specimens with dry moisture levels (MC1, MC2 - batches 1 and 2) formed a cluster, while the specimens with the highest moisture levels (MC3, MC4, MC5 - batches 3, 4,5) were grouped in the other cluster. These groupings may be characterized by the descriptive measurements shown in Table 4 and it was verified that all the variables (X-UPV, Y-UPV, Z-UPV, D, P, CS) influenced these groupings, since the p-value was null for each group. We observed that cluster 1 (the driest) was characterized by having the lowest averages for all the properties (except porosity, which responded inversely) when compared to cluster 2.

Table. 4. Characteristic values of the cluster for each variable.

4. Discussion.

The results of this study show that a relationship exists between different physical-mechanical parameters of a lime-stabilized rammed earth wall, its MC and the respective ultrasonic measurements. Additionally, the statistical analysis revealed that all were closely involved with MC and that it was also possible to form groups without taking into account MC but coherent in their distribution. To discuss the results, we chose to establish the medians per batch of each parameter (Table 5), since this provides a better match than the average given the heterogeneity of the material and the dispersion of certain measurements. Moreover, since statistical analysis determined that groupings and clusters were consistent from the mathematical standpoint, the relationships among all the variables in terms of MC must be strong.

Table. 5. The medians of the values of each batch expressed from left to right as a function of the increase in MC.

Regarding the groupings shown in Table 5, the following aspects can be discussed. First, it can be observed that the specimens could be grouped into low MC (batches 1 and 2: 14.32% and

15.97%, respectively) and high MC (batches 3, 4 and 5: 16.82%, 16.95% and 17.23%, respectively). As shown in Figures 7 and 8, this change in behaviour was also evidenced by the strong increase in density and porosity between batches 2 and 3. Figure 7 also shows that there is no direct relationship between density and CS, as already discussed by Hall and Djerbib [16]. Considering the median density and porosity per batch, we observed that these parameters clearly improved with the increase in median CS. This increase was more evident when considering the jump between low and high MC batches.

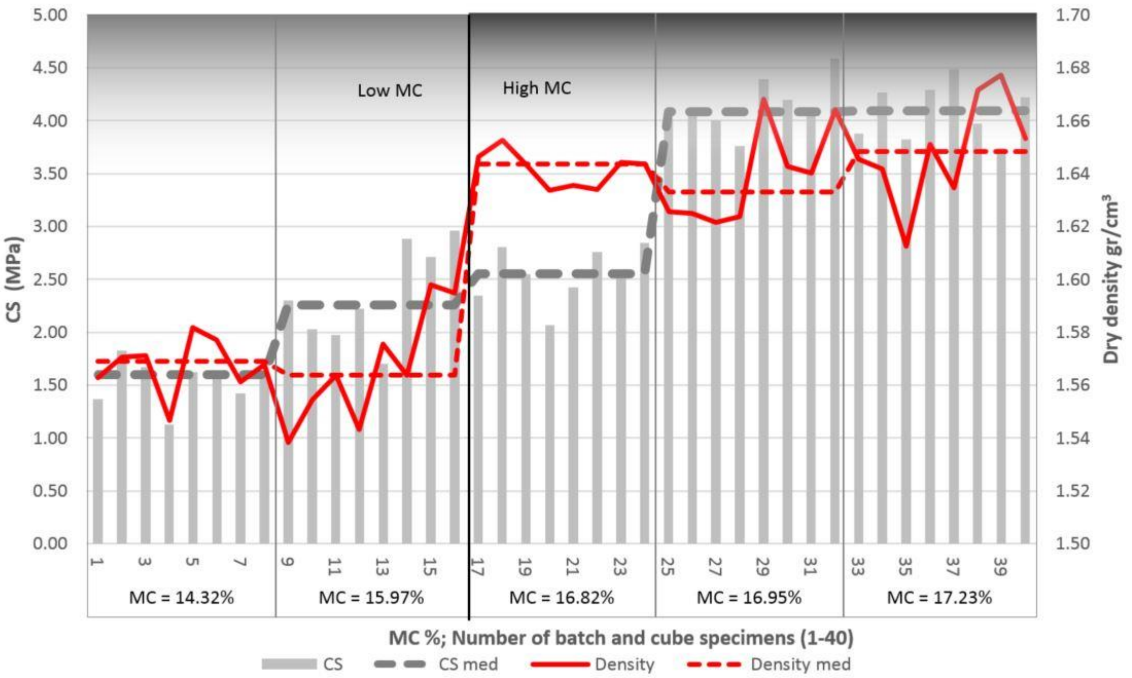


Fig. 7. Representation of density according to batches and specimens.

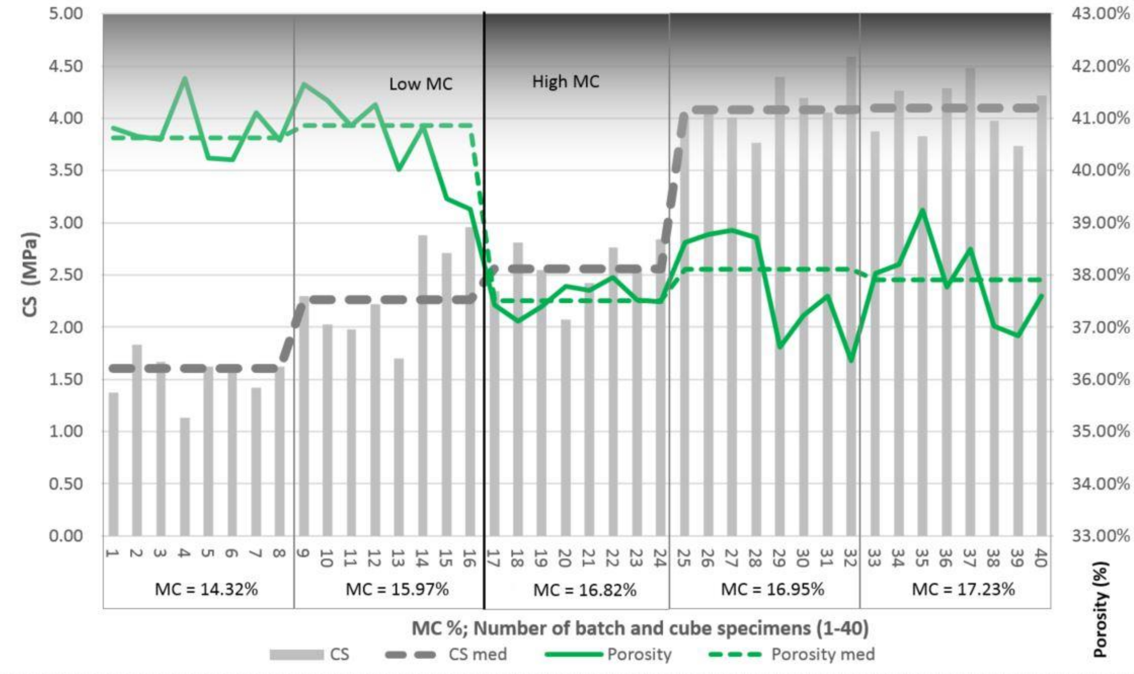


Fig. 8. Representation of porosity according to batches and specimens.

According to Figures 7 and 8, MC was the variable that always increased with the increase in CS. Therefore, having already presented our arguments in the statistical analysis, we can highlight the importance of MC with respect to physical-mechanical properties. Whenever there was a shortage of moisture (batches 1 and 2), in addition to less suction effect, compaction was less efficient for the same specific energy. Thus, for a low MC (up to 85% OM), the characteristic values of D (1.56 g/cm3) decreased up to 7% and those of P (40.8%) were up to 7% higher than when MC was considered high (90% of OM, batches 3 to 5). In contrast, a high MC level was when the maximum values of CS, D and the lowest porosity were reached. However, for batch 3, which presented adequate moisture content and favourable densities and porosities, CS was in a lower range than expected according to batches 4 and 5, although somewhat higher in the dry batches (1 and 2). As will be discussed later, UPV for this batch also corresponded to a high CS (approximately 4 MPa). From the density or porosity standpoint there was no obvious explanation for the low CS in batch 3. A construction defect in batch 3 or another uncontrolled parameter (variation in the type of aggregate or distortion of the PSD) could have caused this anomaly. Furthermore, since MC was not determined by specimen, we were unable to establish the exact degree of involvement with the discordances discussed between CS and density-porosity at individual specimen level.

Likewise, statistics confirmed that ultrasound velocities (X-UPV, Y-UPV, Z-UPV) depended on MC and that their measurements could be classified according to the low and high MC groups (low and high MC corresponded to smaller and larger cluster centres, respectively; see Table 5). In fact, the ultrasound velocities presented in Figures 9 to 11 show a good alignment with the MC levels, with the exception of batch 5 which corresponded to the highest CM (17.23%).

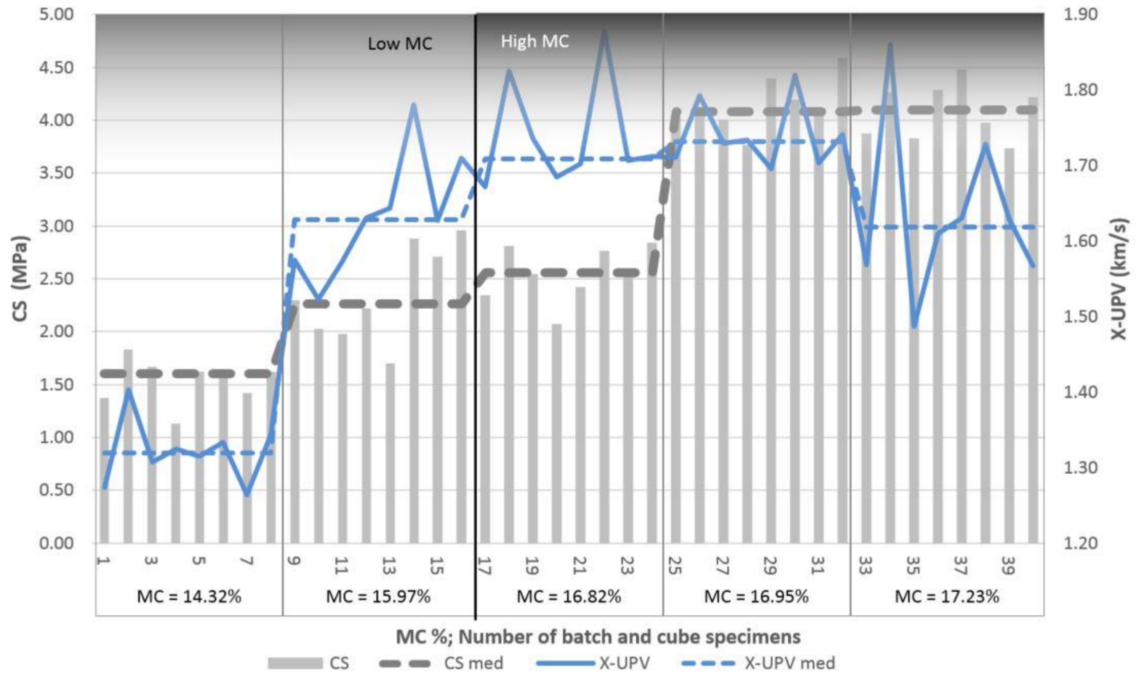


Fig. 9. Representation of X-UPV compared to CS by batches, their mixture moisture content and the specimens.

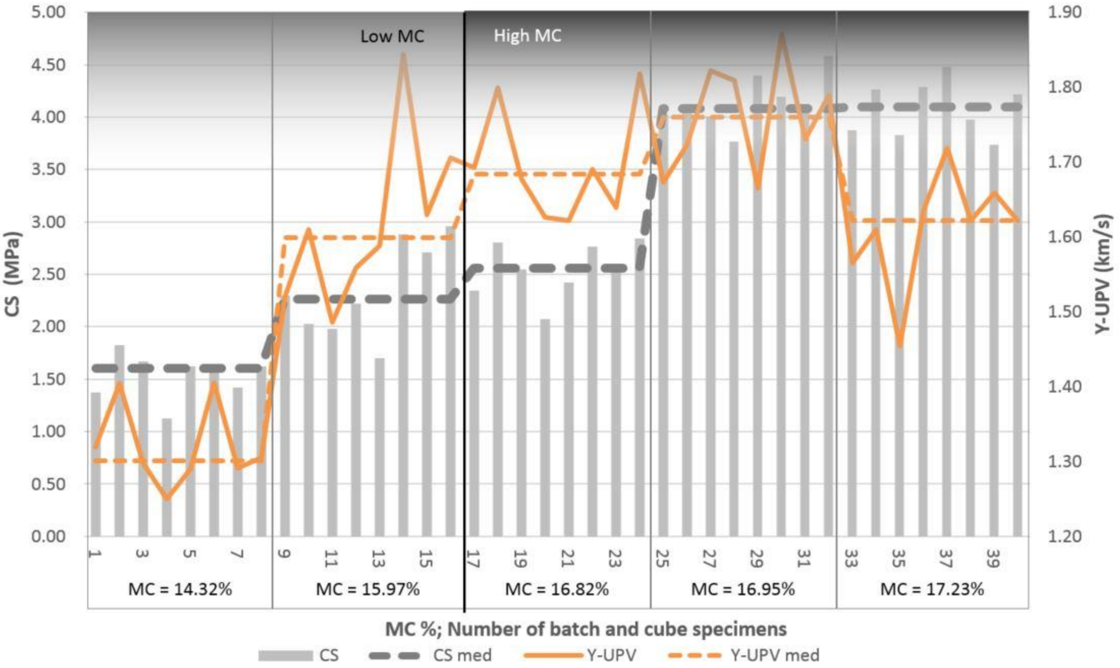


Fig. 10. Representation of Y-UPV compared to CS by batches, their mixture moisture content and the specimens.

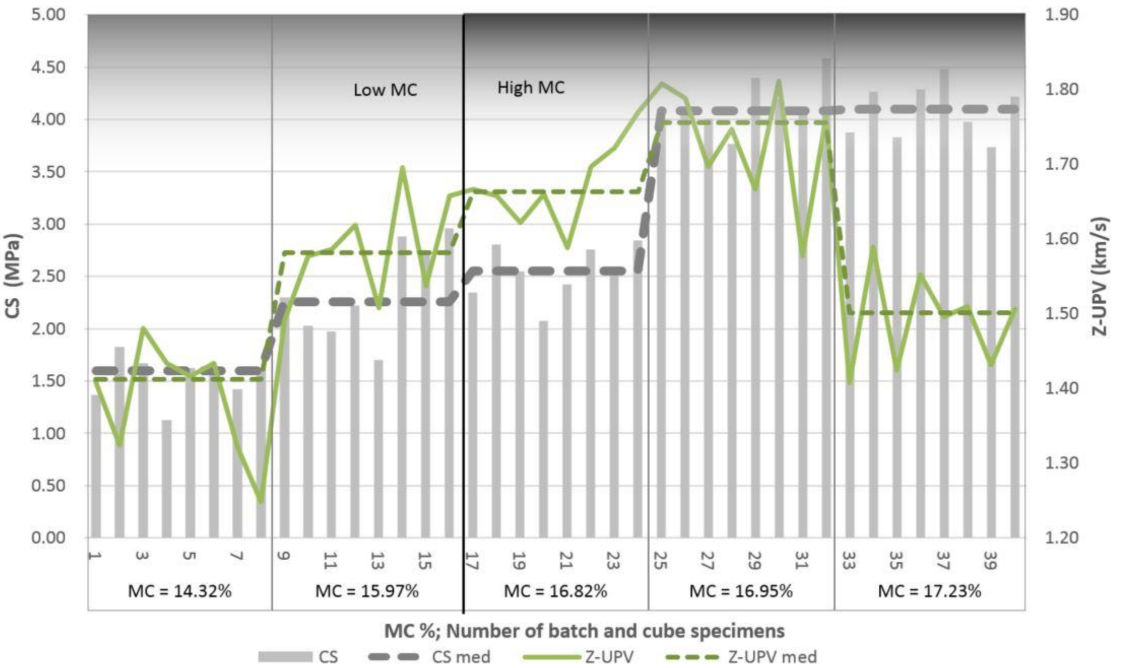


Fig. 11. Representation of Z-UPV compared to CS by batches, their mixture moisture content and the specimens.

With the exception of batch 5, it is worth highlighting that the medians of Y-UPV and X-UPV maintained a good relationship with CS. In fact, for the abovementioned deficiency in CS of batch 3 (it presented median CS levels lower than the median corresponding to the high MC group), the ultrasound velocities of batch 3 were also lower than those of batch 4 within the high MC group. This was not the case with density or porosity, whose medians remained very similar throughout the high MC group. Discarding variations in temperature, shape, density-porosity and size of the specimens or the length of the ultrasound wave path, the most probable causes of the reduction in UPV in batch 3 were a reduction in the moisture content of the sample or the presence of internal discontinuities.

The behaviour of batch 5 for the three UPVs shows that a higher density or lower porosity and a higher CS do not always imply higher ultrasound velocity. The decrease in UPV for batch 5 (MC = 93% of OM), which was more pronounced in the Z direction, was in discordance with the behaviour of the previous variables that remained within similar ranges, and can therefore not be explained by a difference in CS, D or P. A small increase of less than 1% in MC does not seem significant to explain the reduction. This implies that although we were unable to establish a good correlation by multivariate regression between UPV and CS, UPV is a parameter that can be used to estimate the quality of a rammed-earth wall in terms of its mechanical strength. Knowing that UPV depends on, among other things, MC and the porosity of the material [43], it has been demonstrated for other materials with discontinuities or micro cracks that UPV decreases significantly once a critical point of humidity has been reached [42]. This moisture value does not correspond to OM, so the behaviour of UPV will differ from that of density and porosity. This may have been the reason for the reduction in UPV in batch 5, suggesting that the inflection point of MC for maximum UPV is in the range of 17%, compared to 18.5% (OM) for maximum density.

5. Conclusions

This research analysed the physical-mechanical properties and their relationship with ultrasounds for a rammed-earth wall stabilized with lime. The following conclusions may be drawn from the analysis of results:

- As discussed by several authors, the MC of a rammed-earth wall is an important parameter for evaluating mechanical strength. However, much of the mechanical behaviour of this material is determined by the manufacturing process, hence the control of MC is crucial to ensure uniform results are achieved that allow good quality in the execution of the rammed-earth wall. After the application of a statistical methodology, we were able to demonstrate that MC is a parameter that has a decisive influence on density, porosity and CS variables. Therefore, it is important to establish reliable procedures to measure and control this parameter both in the laboratory and on site.
- To summarize, the statistical analyses carried out on the 5 batches of rammed earth specimens allowed us to establish two groups, one with MC under the OM (batches 1 and 2) characterized by low D and CS and high P levels, and another with high MC with respect OM (batches 3, 4 and 5) that were characterized by high D and CS and low P levels. This behaviour may be explained by the fact that when MC is inadequate, in addition to the smaller suction effect, compaction is less efficient for the same specific energy.
- Ultrasound is a complementary non-destructive technique that can be used to qualitatively evaluate the quality of execution of a rammed-earth wall. It has been found that in general, when the CS, D and P variables progressively increase (decrease in case of P) with the increase in MC in the batches, X-UPV, Y-UPV and Z-UPV also increase. However, the behaviour of batch 5 for UPV showed that a higher density or lower

porosity and higher CS do not always entail higher ultrasound speed; hence, a good correlation could not be obtained by multivariate regression between UPV and CS.

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