sustainability

MDPI

Article

Rammed Earth Construction: A Proposal for a Statistical Quality Control in the Execution Process

Jacinto Canivell [1,*], Juan Jesús Martín-del-Río [1], Raúl M. Falcón [2] and Carlos Rubio-Bellido [1]

[1] Department of Architectural Construction II, Universidad de Sevilla, Av. Reina Mercedes 4, 41012 Sevilla, Spain; jjdelrio@us.es (J.J.M.-d.-R.); carlosrubio@us.es (C.R.-B.)

[2] Department of Applied Mathematics I, Universidad de Sevilla, Av. Reina Mercedes 4, 41012 Sevilla, Spain; rafalgan@us.es

* Correspondence: jacanivell@us.es

Received: 21 February 2020; Accepted: 31 March 2020; Published: 2 April 2020

check for updates

Abstract: Unlike other common contemporary construction materials such as concrete, mortars, or fired clay bricks, which are widely supported by international standards and regulations, building with rammed earth is barely regulated. Furthermore, its quality control is usually problematic, which regularly encourages the rejection of this technique. In the literature, many authors have suggested ways to safely build a rammed earth wall, but only a few of them have delved into its quality control before and during the construction process. This paper introduces a preliminary methodology and establishes unified criteria, based in a statistical analysis, for both the production and the quality control of this constructive technique in cases dealing with both samples and walls.

Keywords: rammed earth; quality control; compressive strength; non-destructive testing

1. Introduction

Heritage values, bioconstruction, and sustainability are three factors closely related to rammed earth buildings, which make it an advantageous construction technique that should be preserved and adapted to modern times. Moreover, the low environmental impact of its life cycle assessment makes this technique useful for the development of a more sustainable building sector [1–3]. In spite of this, there are some important obstacles to achieving the full potential of building with rammed earth. On the one hand, it is currently not fully regulated, particularly concerning Spanish regulations. The existing regulations focus mainly only on industrial solutions, and the existing international standards refer to the physical–mechanical requirements of rammed earth. In this last regard, it is very difficult to compare their proposed values, because no standardized procedure exists that determines them uniquely. On the other hand, there are very few quality control tests for using this technique during the construction process. The existing ones have proved to be either unreliable (for example, the so-called drop-test) or too complex to be carried out during works.

Based on these facts, this paper has two main goals. The first consists of presenting an outline of the principal international standards and handbooks concerning building with rammed earth. The second consists of proposing a statistical quality control for before and during the execution of a rammed earth wall. This is based on unconfined compressive strength as the main variable. Due to the high dependence on notations throughout the paper, a glossary is included at the end of the manuscript, just before the bibliography.

2. Quality Control in Standards and Regulations

Not all standards and regulations on earthen construction consider building with rammed earth. Specifically, this technique is mainly considered in regulations in New Zealand [4]; New Mexico, USA [5]; the African Organisation for Standardisation (ARSO) [6]; and India [7]. Furthermore, even if this technique is well-covered by some regulations (for example, the German earth building codes, the Lehmbau Regeln [8]) and some reference texts [9–12], its quality control is not regulated.

In Spain, the only official (but not mandatory) references on the topic are in *Bases para el diseño y construcción con tapial* by the Ministry of Public Works [13] and the prescriptions by the Eduardo Torroja Institute [14]. Furthermore, even if earthen construction is not explicitly discussed in the Spanish Technical Building Code, building with rammed earth walls is possible, although it is much more difficult to be technically implemented and justified.

Before the execution process, it is usually recommended to determine both the dry density *(D)* and the unconfined compressive strength (*CS*). Furthermore, a wide range for grain size distribution *(GSD*) it is suggested (except for NZS [4]), because of its low correlation with physical properties [15]. The optimum moisture content (*OMC*) also appears (explicitly or implicitly), even if all the related tests suggest an alternation between the drop test and some standardized tests similar to the normal Proctor test [16]. Note also the near-absence of control tests to determine plasticity, durability, and erosion, which are usually established once just before the execution process.

During the execution process, the main references [11,12] suggest preliminary studies of each case, but also studies to quantify the control of the entire lot volume. On the one hand, both variables *D* and *CS* are determined by direct methods, mainly through either cored or molded samples. Other procedures (for example, humidity control in the mixing process) are usually suggested and developed by the drop test, which is a qualitative method that may give rise to inaccuracies or errors that cannot be assumed in quality control [17]. On the other hand, even if indirect methods (for example, ultrasound propagation speed, surface hardness, infrared thermography, natural vibration, georadar, or tomography, amongst others) are more agile for the work, they barely appear in the literature and control procedures. Furthermore, unlike other construction materials, there is no statistical quality control of rammed earth, because the commonly applied criteria are mainly based on empirical experience in the field. In short, there is a lack of uniformity in criteria and technical specifications, which are left in the hands of the corresponding expert.

3. Materials and Statistical Framework

As will be discussed, there exists a variety of physical properties that may be analyzed in order to describe the quality control of rammed earth. Based on experience, it has been established [18,19] that all these physical properties, having some influence on some structural security, always obey a stochastic rather than a deterministic variability. Moreover, if sample data are independently taken from each other, then their variation only depends on stochastic causes. As a consequence, they may probabilistically be distributed in a stable way so that their behavior can be predicted under identical experimental conditions. Particularly, if the sample size is large enough (at least 30 samples), the Central Limit Theorem states a normal distribution for the data. This is indeed the probabilistic distribution that is established in the literature to standardize the quality control of concrete [18,19]. This constitutes in turn the model that the current study follows as a reference.

More specifically, this paper focuses on the analysis of the stochastic behavior of rammed earth by means of the random distribution of the variable *CS*, which has been dealt with in the literature [4,20–22]. It is proved in particular that this variable follows a normal distribution when rammed earth is built under controlled conditions. In order to do it, and based on the Central Limit Theorem, it was decided to make use of 48 samples that were made by mixing a stabilized soil with 10% hydraulic lime having their *GSD*, maximum *D* and *OMC* according to the normal Proctor test, as shown in Figure 1. The variable *OMC* was established for the complete dosage in accordance with [16]. The soil plastic limit test was executed according to [23], with a result of 16.6%. Moreover, the liquid limit determination was executed according to [24], with a result of 19.1%. Hence, the plasticity index was 2.5. Attending to the Casagrande's plasticity chart, the soil corresponded to inorganic low plasticity silt. The mean molding moisture content (*MMC*) for all mixes was 11% ± 2%. The moisture content (*MC*) was established within the interval 1.6% ± 0.5%, which constituted an indicative of a similar *MC* for all test samples. These values served as a reference to be followed during sample production.

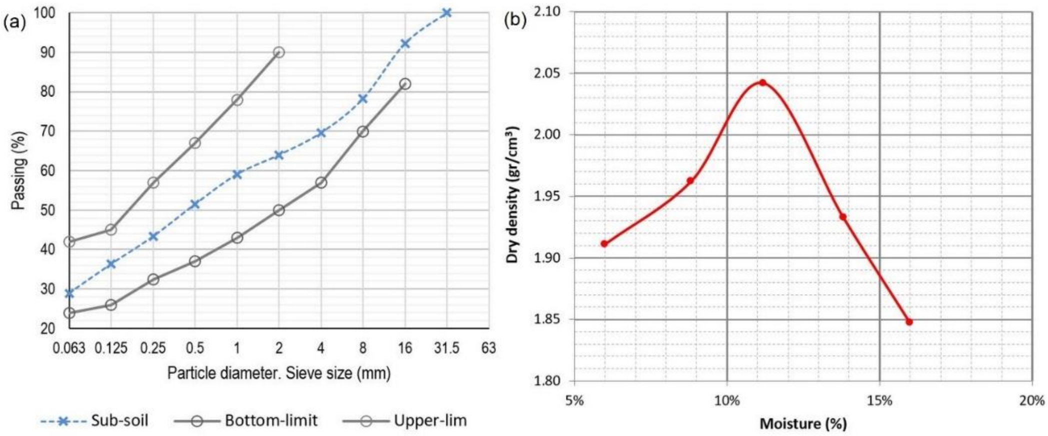


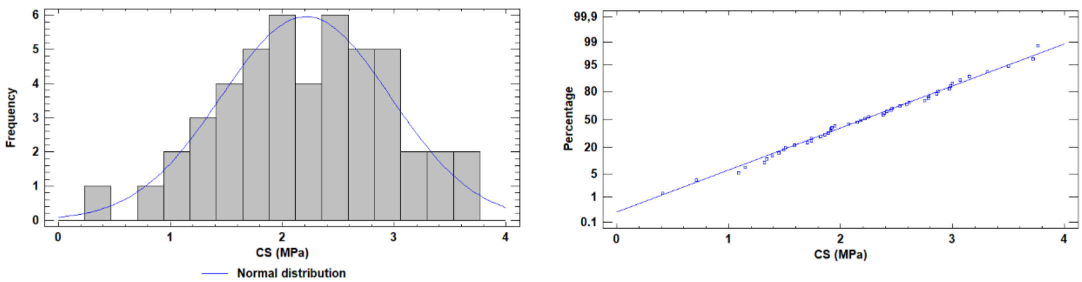
Figure 1. Particle grading curves for sub-soil (**a**) and the Proctor test (**b**).

Table 1 shows all the values of the random variable *CS* (MPa) related to the 48 samples. The standard deviation of these samples is $\sigma = 0.76$.

Table 1. Summary statistics of all variables under study.

Samples	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
CS (MPa)	2.75	2.61	1.74	1.7	2.87	3.07	2.18	1.49	3.50	2.53	2.39	1.59	3.31	3.72	3.76	2.97
Samples	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
CS (MPa)	2.78	2.59	2.46	1.82	1.09	2.15	1.15	1.74	1.91	1.92	1.86	1.91	1.51	2.22	1.45	2.45
Samples	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
CS (MPa)	2.41	1.95	3.15	1.39	0.41	0.71	2.07	2.79	1.32	1.89	3.00	2.98	1.34	2.86	2.38	2.25

Furthermore, the similarity of the sample distribution with respect to the normal one can be observed from Figure 2a. In this regard, the normal probability plot in Figure 2b shows how the 48 sample data concerning the random variable *CS* are always close to the data straight line fitting the normal distribution. Moreover, the chi-square goodness-of-fit test between both distributions gives a Pearson correlation (p-value) of 0.9797 > 0.05, and, hence, it cannot be rejected with 95% confidence that the sample derives from a population following a normal distribution.



(**a**) (**b**)

Figure 2. Histogram (**a**) and normal probability plot (**b**) of *CS* (MPa).

As demonstrated, it is always possible to make a statistical control of the variable *CS* when the on-site production is controlled. Hence, it is necessary to establish the lot size and the sampling rate for rammed earth structures. As will be explained later, the criteria for determining such values are shown in Table 2 and are adapted to a standard on-site production of rammed earth. The main reference for this was the standardized statistical control system for fresh concrete [25].

Table 2. Criteria for establishing both the lot size and the sampling rate for rammed earth structures.

Rammed Earth Volume	**100 m^3**	
Execution time	4 weeks (20 days, 8h/day)	
Built area	100 m^2	
Number of floors	1	
Number of batches	$V_{LMS} \leq 500$ liters $V_{LMS} > 500$ liters	500 batches 200 batches
Soil type	One lot per each different type of soil	
V_{LMS}: Usable volume of the mixers in terms of loose volume of soil (liters)		

Unlike the production of concrete, which is always made in a factory (either with or without a quality label), the elaboration of the structural components of a rammed earth wall is usually carried out on site. Moreover, the volume of fresh concrete that may currently be mixed and transported is higher than that of a rammed earth wall. Thus, a concrete mixing truck, whose capacity is usually considered as a batch, is capable of transporting and/or mixing a useful volume of 8–10 m^3. However, the most common systems for mixing rammed earth materials move in a smaller range, from 0.75 m^3 (forced action pan mixer of 750 liters) to 0.1 m^3 (drum mixer of 100 liters). Additionally, since the material for the wall is usually more heterogeneous, its variability among batches may be greater, and, hence, the quality control conditions must be adapted. Concerning the execution time, the performance or productivity plays an important role in the management and planning of the quality control of concrete. If the performance of a rammed earth wall described in [11,15,26,27] is considered, then an average of 1.6 hours/m^3 of wall may be established by means of modern execution processes as continuous formwork systems, auxiliary means, and mechanical compaction.

The term lot size is introduced to judge the acceptability of a quantity of rammed earth that is executed in the worksite. A lot consists of a certain number of rammed earth batches. Several standards, guides, and authors have proposed different lot sizes depending on the volume of the rammed earth wall. For instance, New Zealand standards (NZS) [4] suggests developing a *CS* test for each 50 m^3 of planned volume of wall, which is similar to the range stated in the Lehmbau Regeln [8]. A more reduced range (5 to 25 m^3) is considered by Walker et al. [9], which differs from the Australian Standards [28], from 25 to 100 m^3. Keeping in mind the previous references, together with the regulation of structural concrete [25], a larger lot size is considered in the current study in order to match the described productivity and a logical period of time, as will be discussed further in detail. This is due to the normal distribution behavior of this material. In any case, practitioners could always adapt this proposal to the exact conditions of their worksite.

In order to establish a suitable lot size for rammed-earth production, a minimum reference module is also defined, which can be repeated in cases dealing with larger buildings. Taken as a benchmark is the execution of a 100 m^2 building on one floor (10 × 10 m), which is equivalent to the standard size of a minimum residential unit of 80–90 m^2 [29]. Walls are established to be 50 cm thick and three meters high, plus their corresponding gables. As a consequence, an approximate volume of 100 m^3 of wall is considered (except for openings) as the reference for the quality control. From the already mentioned average productivity, this volume constitutes 160 working hours; that is, four intensive weeks of five working days and eight daily hours. These criteria are shown in Table 2. This differs from the standardized two weeks for a concrete lot corresponding to compressed elements (see Table 86.5.4.1 in [25]). In short, the proposed conditions to define a lot of rammed earth wall are:

1. A volume of 100 m^3.
2. A period of execution of four weeks.
3. A built area of 100 m^2.
4. One single floor.

Under these conditions, the site technical manager may interpret the number of lots that are required to define a quality control according to the particular conditions of each work. From Table 2, two categories of mixers are established. The smaller ones of 500 liters are the most common in the production of rammed earth, and because of this they constitute the reference for controlling the execution process under more standardized conditions. Thus, in cases dealing with a mixer with a useful volume of 250 liters in reference to the loose volume of material (whose compaction percentage for clayey-sandy soils is usually 20%–30%), the volume of compacted material holds Equation (1):

$$V_{CMS} = V_{LMS}(1 - \%C_L), \tag{1}$$

where V_{CMS} is the usable volume of the mixer in terms of the compacted volume of soil (m^3), V_{LMS} is the usable volume of the mixers in terms of the loose volume of soil (m^3), and CL is the compaction coefficient of a loose volume of soil.

Once the 100 m^3 lot is established as control volume, approximately 500 batches would be required for the described mixer. It is also necessary to establish the number of batches that may be considered as representative over this normally distributed population. Note in this regard the existence in the literature of different formulas for determining the most convenient sample size to be used in the context of a given experiment (see, for instance, Chapter 2 in [30]). Thus, in cases interested in the sample size associated to the maximum possible error of estimation, the following Equation (2) is widely used (see Equation (2.10) in [30]):

$$n = \frac{N\sigma^2 Z^2_{\alpha/2}}{e^2(N-1) + \sigma^2 Z^2_{\alpha/2}}, \tag{2}$$

where, in the context of the current study, n is the number of controlled batches, N is the total number of batches (N = 500), σ is the standard deviation ($\sigma = 0.76$), $Z_{\alpha/2}$ is the critical value depending on the confidence level ($Z_{\alpha/2} = 1.65$ for a 90% confidence level), and e is the acceptable limit of the sampling error ($e = 20\%$).

These explicit values give rise in Equation (2) to $n = 36$ controlled batches. They correspond approximately to two daily batches randomly taken from the daily executed ones during the four weeks of the execution process of the 100 m^3 of rammed earth wall. Under these conditions, the quality of the execution process may be ensured with a 90% confidence level. Moreover, these 36 controlled batches are used for the control of the product.

By following the recommendation of the Australian Standards [28], and in order to get a normal quality control, it was also established to make two samples from each randomly controlled batch. In the case under study, the minimum number of statistically representative samples is 72. Furthermore, the site technical manager could make different control decisions depending on the specific conditions of each work. In this regard, a reduced control level could also be considered, whereby only one sample per batch would be made from each one of the 36 minimum controlled batches. Thus, the total number of samples over which the variable *CS* would statistically be evaluated is at least 36, thus exceeding the already mentioned 30 individuals established by the Central Limit Theorem.

4. Proposed Methodology for Quality Assessment

The first step of the proposed methodology consists of distributing all those tests that are described in the literature for controlling the quality of rammed earth wall components. To this end, each test is classified according to whether it is made before (first stage) or during (second stage) the execution process. In the first case, the test under consideration usually determines physical–mechanical parameters depending on available raw materials. In the second case, it usually determines the compliance with benchmark values that are established during the first stage. In both cases, every test is carried out either on materials (soils or mixed dosage) or products (samples, wallets or finished walls). Used tests and sampling frequencies are shown in Tables 3–6, where a normal control level is always considered. When circumstances are described as unfavorable by the corresponding technician (because of poorly qualified labor, deficient auxiliary means, adverse weather conditions, or high-quality requirements), it would be necessary to review sampling ratios, their frequency, and the number of individuals or readings.

Figure 3 shows a workflow of the proposed methodology. Both the first and second stages are represented at the top and bottom of that figure, where the definition of the lot size and the number of batches to be controlled appear just before the initiation of the construction work.

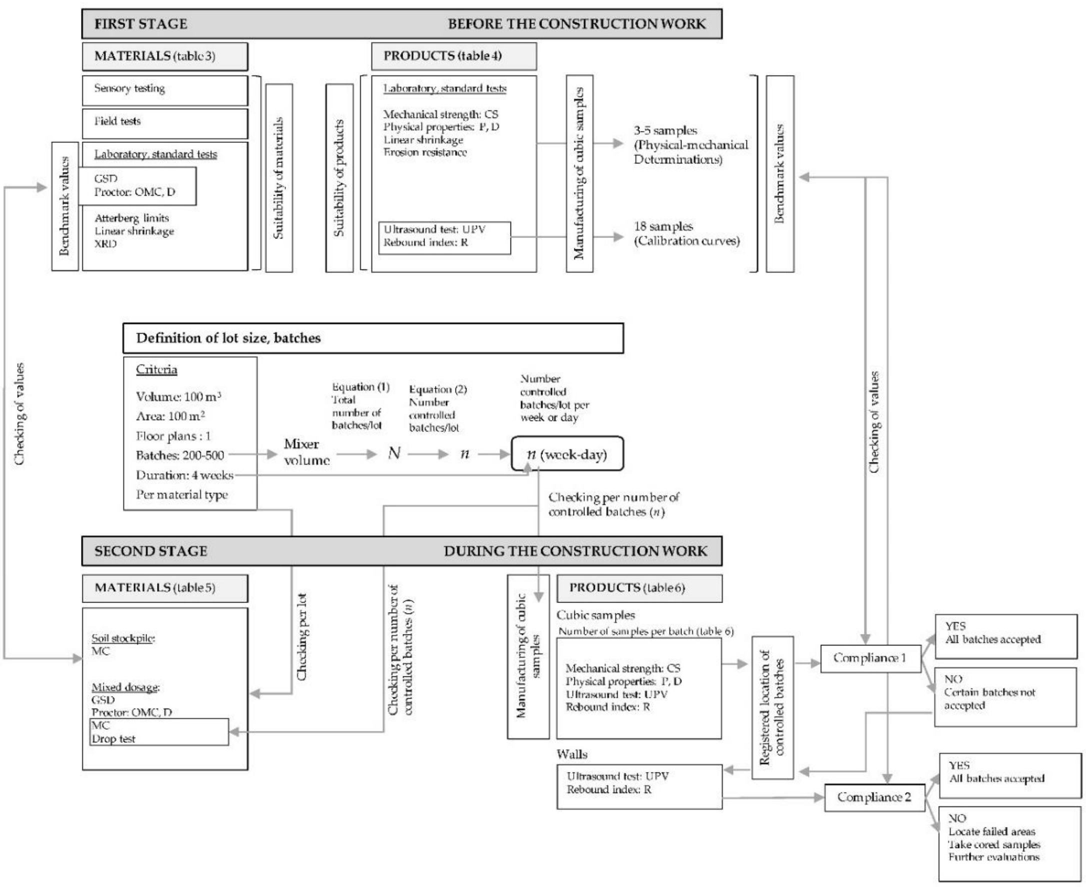


Figure 3. Proposed workflow for quality control methodology.

The first stage is addressed to design and confirm the suitability of construction materials and also to set the benchmark values that are used during the second stage. Some of these values are obtained from the manufactured cubic samples by following the procedure described in Section 4.2. In this case, only a sufficient number of samples are made to determine certain characteristic mechanical or physical values. This number (n) of controlled batches is determined by means of the procedure described in Section 3 and the criteria described in Table 2, together with the usable volume of the mixer that is employed during the construction work.

The second stage also deals with the analysis of both materials and products. For the former, suitability is checked according to the benchmark values that have previously been set in the first stage. Certain values, such as the variable *MC* associated to the soil stockpile, the *GSD*, and the already described *D* and *OMC*, are checked according to a lot criterion, while the variable *MC* of the mixed dosage should follow the number of controlled batches (*n*). Concerning the control of products, the same manufacturing process from the first stage is now proposed to develop a statistical control based on the variable *CS* of the production of rammed earth. The value *n*, which was set according to the circumstances of the worksite, is therefore considered to control the number of representative batches from the total population of each lot (*N*). As it will be explained in Section 4.4, the sampling of each controlled batch could be modified depending on the evaluation of the site technical manager. Every controlled batch should firstly be registered and located in order to facilitate the remark of certain built volume. As shown in Figure 3, the compliance of the values is obtained from the mechanical testing of the samples according to the reference values that have been described during the first stage. In case of not reaching these benchmarks, some complementary tests are proposed to be carried out (for instance, ultrasound and rebound index) in order to develop further analysis.

4.1. Laboratory Testing of Rammed Earth Material Before the Construction Work

Before the execution process, it is crucial to evaluate the suitability of materials in order to establish the benchmarks that are subsequently required during the work on site. In particular, a representative sample has to be obtained from each type of soil, as indicated in Table 3, in order to determine certain properties implying the rejection or acceptation of raw materials, and, thus, to determine the appropriate dosage.

For each step of the execution process, all the tests have been classified as compulsory (*CO*), recommended (*RE*) or optional (*OP*). Here, the compulsory tests carry out the minimum scale of an accurate quality control, while the recommended tests provide complementary information (such as non-destructive tests) that may be included in a quality control plan if the basic parameters are not reliable enough or the executed elements have to be evaluated. Finally, the optional tests re considered when the scale of the building requires extra information or if the development of compulsory analyses are not feasible.

Initially, sensory and field tests may be carried out in a qualitative and quantitative way to roughly determine the main properties of the soil. Several authors propose similar methods as visual, touch, smell, exudation tests, ribbon tests, dry strength tests, or sedimentation [10,31]. To this end, it is usually necessary to consider, after soil cracking, a total sample of about 10 kg, which is also used to carry out laboratory and standard tests.

A second group includes standardized tests, among which *GSD*, organic matter content, plasticity, and mineralogical composition stand out. Note in this regard that *GSD* [32] is essential in this first stage, because it makes it possible to accept or correct aggregates in a soil sample by comparing both the distribution and percentage of their sizes with some reference curves [9,20,33]. Further, it must be taken into account that there is no single ideal particle size distribution for earthen construction because each technique requires its own specifications. In cases dealing with rammed earth, it is possible to design a specific distribution according to Fuller's ideal curve adapted to the case of natural soils [34]. Some authors also discuss that *GSD* should not be the only reference for predicting the suitability of a soil for building a rammed earth wall [20].

In order to determine the clay content, both a density meter [35] and XRD mineralogical analysis may be used. Note that the presence of organic matter should be limited to avoid the deterioration processes and the loss of material durability. In this regard, Schulte and Hopkins [36] introduced a method to determine the organic matter content by means of loss on ignition, which is limited to 2% [37,38]. Unlike some other field tests that also detect the presence of organic matter, the latter is objectively quantified by this method.

Table 3. Proposed laboratory quality control for rammed earth materials before the construction work.

Soil Test	**Information**	**Values**	**References**	**Type**	**Rates**	
Sensory testing						
Visual, touch, and smell	Type of aggregate and clay	Overall type of soil: texture, presence of organic matter, clay, fines, and aggregates	[31]	OP	1 sample of 1 kg/soil [1]	10 kg of soil
Qualitative tests						
Exudation test	Fine content	Presence and activity of clays: certain presence of fines and low activity	[31]	OP	1 sample of 0.5 kg/soil [1]	
Ribbon test	Cohesion	The ribbon should break at certain length	[31]	OP	1 sample of 0.5 kg/soil [1]	
Dry strength test	Cohesion and hardness	The force to break the sample should not be high	[31]	OP	1 sample of 0.5 kg/soil [1]	
Sedimentation	Overall distribution of aggregates	Not excessive presence of fines	[31]	OP	1 sample of 0.5 kg/soil [1]	
Laboratory tests						
Grain size distribution (GSD)	Curve of particle size distribution (% passing)	Depending on the source: Aggregate (45–80) Silt (10–30) Clay (5–20)	[9,32,34]	CO	1 sample of 4 kg/soil [1]	
Calcination	Organic matter content (%)	Without presence	[36]	RE	1 sample of 10 g/soil [1]	
Atterberg limits	Liquid, plastic limit. Plasticity index	LL < 35–45IP < 10–30	[20,23,24]	CO	1 sample of 0.5 kg/soil [1]	
Linear shrinkage	Δl/l (%) Linear degree of shrinkage	< 0.5–2%	[8,9]	RE	1 sample of 0.5 kg/soil [1]	
XRD	Mineralogical composition	Qualitative and semi-quantitative type of minerals	[39]	RE	1 sample of 0.5 kg/soil [1]	
Dosage Test	**Information**	**Values**	**Ref.**		**Rates**	
Standard tests						
Standard Proctor	D (g/cm^3), OMC (%)	Depending on the soil. Usually: D = (1.8–2.5) (g/cm^3) OMC = (10–20)%	[16]	CO	1 sample of 15 kg/soil [1]	
Modified Proctor	D (g/cm^3), OMC (%)		[40]	CO	1 sample of 35 kg/soil [1]	

Note: [1] Every type of soil should be tested. CO: Compulsory; OP: Optional; RE: Recommended.

As suggested by various authors, it is necessary to establish the plasticity of fines. To this end, the liquid [24], plastic [23], and plasticity index limits are analyzed within certain margins [20]. Once the latter have been established, the soil can be modified or chemically stabilized with the addition of an optimum percentage of lime, according to either its relationship with the plasticity index [41] or Portland cement [15], or physically by adding some specific aggregate fractions to improve the compactness of the *GSD*.

Analytical techniques based on XRD [39] are not essential, although they can provide qualitative and semi-quantitative information on soil minerals, such as the type of clays. Other techniques, such as X-ray fluorescence and/or X-ray microfluorescence, enable the identification of the chemical composition of such material. For the correct performance of these tests, it is essential to take a representative sample by means of a convenient quartering process.

Finally, the chosen dosage (soil, binder and additives), the maximum *D* and the random variable *OMC* are essential for establishing subsequent performance tests. They are determined by means of the normal Proctor test—manual compaction—[16] or the modified one—mechanical compaction—[40], with their equivalent Anglo-Saxon standards [42–44]. For this purpose, a representative sample of 15 kg or 35 kg of soil, respectively, shall be taken at the time of the test. Previous studies [45] give values for the variable *D* around (1.8–2.5) g/cm^3, and for the variable *OMC* around (9 – 20)% for normal Proctor compaction energy.

4.2. Laboratory Testing of Rammed Earth Products Before the Construction Work

Once the dosage of the wall has been described, tests should be carried out in two stages: before execution for defining physical–mechanical properties, and during execution for controlling how all these properties are preserved (see Table 4, which also includes the thresholds for accepting or rejecting the processed product). Previously, the description of a procedure has been required for making samples in the laboratory by simulating execution on site.

In order to determine certain physical–mechanical parameters by means of tests made before the execution process, a sufficient number of samples are suggested (Table 4). In this regard, Ciancio and Gibbings [46] recommended at least five samples to compute the variable *CS*. Before carrying out the *CS* test, these samples are also used to determine the values of some other variables as *D* and porosity (*P*), together with other complementary test like ultrasound pulse velocity (*UPV*) and rebound hammer.

Concerning quality tests for products, the determination of both variables *D* and *P* provide important data for controlling both the compactness and durability of the rammed earth wall under construction, even if it is not definitive for the mechanical strength [21]. Since no regulation exists for rammed earth, the existing one for stone (which has already been proposed and successfully proven [47]) is assimilated to determine the variable *CS* [48]. More specifically, this analytical technique is made on small sections extracted from a 15 cm x 15 cm x 5 cm prism (which is termed sample B from now on), subjected to vacuum and immersed in water. These sections are weighed for determining some physical properties like real or dry density, or porosity. Note that this technique is feasible and accurate for lime or cement stabilized rammed earth. However, for non-stabilized types of rammed earth, or even other materials such as adobe or cob, it would be necessary to redesign the previous experiment by immersing them in a solvent such as White Spirit, in order to prevent samples without chemical stabilization from being dissolved in water. In that case, the density of the dissolvent (700–800 kg/m^3) should be considered in order to obtain accurate values.

Table 4. Proposed laboratory quality control to rammed earth products before the construction work.

Sample Test	Information	Values	References	Type	Rates
Unconfined compression strength	Mechanical resistance. *CS* (N/mm^2)	Variable depending on the reference. *CS* > 1–1.5	[49]	CO	5 Type-A samples/soil [1]
Porosity and dry density	Quality estimation. *P* (%) *D* (gr/cm^3)	Soil variable. *P* = (30–40)% *D* = (1.5–2.8) (gr/cm^3)	[48]	CO	5 Type-B samples/soil [1]
Ultrasonic pulse velocity	*UPV* (km/s) Quality estimation (compactness).	Highly variable. *UPV* = (1–3) km/s (10% lime-stabilized)	[49,50]	OP	5 Type-A samples/soil [1,2]
Rebound hammer	Surface hardness. Quality estimation. Rebound index (*R*).	Highly variable. *R* = 30–80 (Schmidt OS-120PT) (10% lime-stabilized)	[49,51]	OP	5 Type-A samples/soil [1,2]
Linear shrinkage	Δl/l (%) Linear degree of shrinkage	< 0.5–2%	[8,9]	RE	3–5 samples type A or B/soil [1]
Erosion resistance	Erosion depth and index (mm/min)	< 2	[4]	RE	2 samples type A or B/soil [1]

Note: [1] Every different type of soil should be tested. [2] At least 18 samples are required to obtain a calibration curve for each type of soil or dosage. CO: Compulsory; OP: Optional; RE: Recommended.

Concerning non-destructive tests, ultrasound is a complementary technique that can be used to compare the quality of execution of a rammed earth wall [45]. Even if it can be used as an indirect method to evaluate the mechanical strength evolution of the rammed earth wall, it requires, however, the use of direct correlation among samples. To this end, a regression is established between both variables *UPV* and *CS* for at least 18 samples [49]. In this way, a material calibration curve is generated, which will be used during the execution process in order to establish the variable *CS* in situ, whenever the conditions of the already constructed rammed earth wall are similar to those ones of the samples.

Ultrasonic tests are performed on cubic A-type samples with an Ultrasonic-Tester by following the procedures in the UNE-EN 12504-4 standard [50]. It is recommended, whenever possible, to take measurements in all three orientations *X*, *Y*, and *Z* (see Figure 4a) and at least four readings on each face. These readings are valid if the variation is within ±10% of the mean. This criterion is considered for determining the ultrasonic pulse velocities *X-UPV* and *Y-UPV* for those directions that are perpendicular to the compaction direction, and *Z-UPV* for the compaction direction.

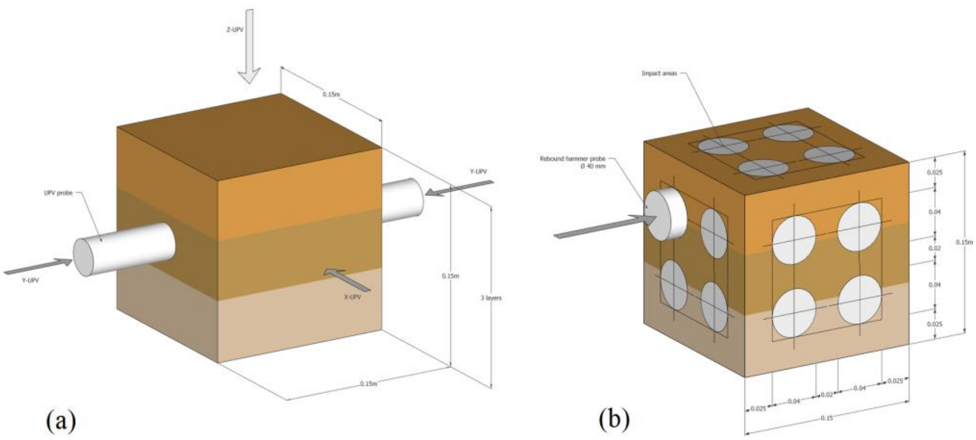


Figure 4. Location of ultrasonic pulse test tubes (**a**) and placement layout of impact areas for rebound test (**b**).

The rebound index (*R*) determination is another indirect non-destructive method that, only by itself or combined with ultrasound, may assess the quality of a rammed earth wall [52,53]. This technique is based on a surface hardness test that is made by means of a suitable equipment for soft materials, which is similar to the Schmidt OS-120PT pendulum hammer. Note from [51] that the 15 cm cubic samples (which are termed A samples from now on; see Figure 5) required at least nine valid readings distributed on their non-irregular faces and separated by 25 mm from each other and from the edge (see Figure 4b). Here, less than 20% of the readings differ more than 30% above the mean. Similar to the calibration curves that were previously obtained for the variable *UPV*, new calibration curves are determined now for each type of soil by means of 18 new pairs of values related to both the variables *R* and *CS*. In particular, the values related to the variable *CS* are determined at 28 days aging by using an electromechanical strength testing machine. Here, all the A samples are dried and had a similar moisture content. Then, the test is carried out in the direction of compaction, because of the possibly different behavior in the other orthogonal directions [54]. Furthermore, according to the standard UNE-EN 12390-3 [55] for hardened concrete, if the cubic sample shows irregularities on the face of compaction, then it should be capped with cement-rich mortar (taking care that this mortar does not add excessive moisture) or with sulfur mortar. Several studies have suggested the use of steel platens in direct contact whenever the faces of the samples are flat enough. In such cases, the mechanical test is carried out with a loading rate of 300 N/s and breaking times of 30–90 s, by following the procedure described in [56]. This value corresponds to the interval established for mortars from 5 N/s to 500 N/s, which was also proposed by Hall and Djerbib [21].

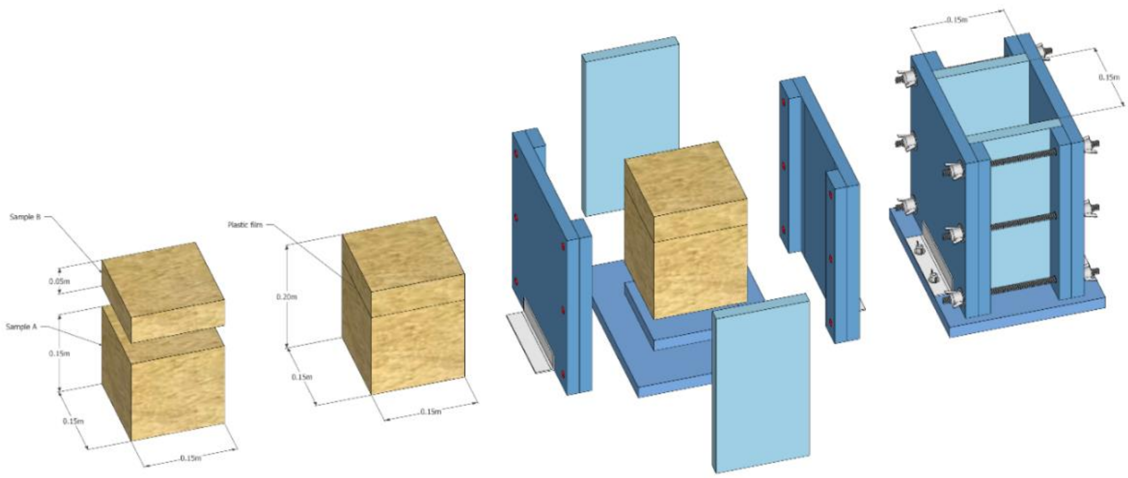


Figure 5. The mold proposed to make test tubes for rammed earth walls.

Linear shrinkage [8] and erosion [4] are another two tests that estimate the product quality and may constitute criteria for direct rejection of a dosage. The former is important to avoid excessive cracking during drying, whereas the latter enables one to assess the long-term behavior of a rammed earth wall that is exposed to the weather.

In the literature, both cylindrical [46,57–59] and cubic [21,54,60] samples have been proposed with various dimensions and slenderness. In the current study, a 15 cm x 15 cm x (20–30) cm prismatic mold is proposed (see Figure 5). This is easier to make and offers flatter faces that are suitable for non-destructive tests (as ultrasonic and rebound index) [45]. Moreover, its larger size enables a more cost-effective use of the soil and enables samples to be more similar to those walls that are made on site. In any case, maximum aggregate size restrictions must be applied [61] so that it should be less than one third of the diameter of the sample edge size. In cases dealing with prismatic molds, a 15 cm cube (sample A) should be obtained for computing the variable *CS* and one of at least 5 cm high (sample B) for determining some physical properties (like real and *D*, and *P*).

Table 5. Proposed quality control to rammed earth materials during the construction work.

Soil Analysis	Information	Values	References	Type	Frequency
Tests					
Grain size distribution (GSD)	Aggregate distribution curve (%)	Soil variable. Aggregates (45–80) silt (10–30), clay (5–20)	[9,32]	CO	1 sample 10 kg/lot [1]
Moisture content	Soil moisture before mixing	Compare with *OMC*	[62]	RE	3–5 samples 200 g/lot [1, 2]
Dosage Analysis	**Information**	**Values**	**References**	**Type**	**Frequency**
Tests and field trials					
Moisture determination	Moisture content after mixing	Compare with *OMC* (Table 3)	[62]	CO	200 g 3–5 sample/batch [4]
Drop test	*OMC* estimation	Qualitative values Partial breakage into pieces (3)	[4] (Apend. G)	RE	200 g sample/batch m^3 [3]
Proctor normal	D (g/cm^3) *OMC* (%)	Soil dependence D = (1.8–2.5) (g/cm^3) *OMC* = (10–20)%	[16]	OP	1 sample 15 kg/soil [1]
Modified Proctor	D (g/cm^3) *OMC* (%)		[40]	OP	1 sample 35 kg/soil [1]

Note: [1] Carry out the test if the origin or nature has changed with respect to tests done before the execution process. [2] Keep the stockpile isolated from moisture variations. If necessary, then check whether the soil stockpile moisture has changed in order to adjust the water that is added for mixing. [3] The drop test should not be used alone to evaluate the variable *OMC*. [4] If soil storage conditions require the moisture to be maintained, then *MC* may be controlled for every 10–50 m^3. When mixing is carried out in the factory, the frequency is increased to one test for every 50 m^3 of executed rammed earth wall. CO: Compulsory; OP: Optional; RE: Recommended.

In order to control the sample processing, it is recommended that the sub soil have uniform moisture content either by drying it in an oven or by aeration for 24 hours. The MC of the dry soil is then determined [62] so that the precise amount of water can be added to more accurately achieve the OMC. This is crucial when several batches of non-simultaneous samples are taken.

A dry mixing of rammed earth components should firstly be run by mechanical or manual means. Once the batch is utterly uniform, the precise water to reach the determined *OMC* is sequentially added. In this step, the initial moisture of the soil should be deducted from the considered *OMC*. Minke [10] suggests that up to 10% extra moisture over *OMC* may produce higher *CS*. Thus, if water is lost during mixing, then it is always better to exceed *OMC* in some way. In cases using mechanical mixing, note that tilting drum mixers are not best suited for dry consistencies and may produce inhomogeneous kneading. In this case, the manual method is more effective, although also time consuming.

It is recommended to design each batch (corresponding either to the laboratory or to the work on site) for the same number of samples. It is also necessary to determine, by means of drying in an oven [62], the humidity of at least three samples of about 100 g from the inside of the mix. Note that, since drop tests have been proved to be unreliable to verify *OMC* [17], other laboratory methods should be used to get an adequate quality control in terms of the variable *MC*.

Even if it is more time consuming, the compaction method that is proposed in the current study is the manual one. Similar to the traditional constructive system, it gives rise to an adequate control of the compaction energy and avoids reinforced molds. Based on some existing descriptions in the literature [11,12,63], the selected rammers have a prismatic head of 8 cm x 8 cm x 20 cm and 2.5 kg (which is useful for internal compaction) and wedge-shaped for corners. However, samples have also been mechanically produced by using a variable speed jackhammer with an impact energy of 1–3.5 joules per blow, which is equivalent to the compaction degree of manual methods. In this case, recommendations from [20] may be followed to obtain the equivalent compaction energy.

Since manual means are addressed, the objective here is to achieve the best uniformity among samples by determining the number of strokes (n) of the rammer for each layer in order to reach the maximum density of the Proctor test. The proposed procedure is similar to those ones described in [20,46]. Firstly, the ratio between compaction energy and volume is established, which is the specific compaction energy (e_s). Then, it is compared with the specific compaction energy (e_{OMC}) of the standard Proctor test [16]. This relationship is described by the following Equation (3):

$$e_s = e_{OMC} = \frac{Er(h, W)}{V_l}, \quad (3)$$

where $E_r(h,W)$ is the energy generated by the fall of a rammer of weight W from a height h and V_l is the layer volume.

In particular, the energy $E_r(h,W)$ derives from the following Equation (4):

$$E_r = (W \times g \times h)\, s, \quad (4)$$

where, since manual ramming is applied, s is the number of strokes that are required to achieve the reference compaction energy, g is the acceleration gravity value, and h is the free-fall height of the rammer.

As a consequence, the number of strokes s that are required to achieve a specific energy of compaction e_s is determined by the following Equation (5):

$$s = \frac{V_l \times e_{OMC}}{W \times g \times h} \quad (5)$$

Note in any case that even if this last expression enables one to adapt the calculation for any configuration, non-compacted layers should not be greater than 15 cm.

Strokes are distributed over the layer surface by taking into account the dull sound when the number of strokes *n* is reached. Ideally, a 15 cm cubic sample should consist of three complete layers (see Figures 5 and 6). Then, the next layer completing the prism may be made by means of a flexible separating layer, allowing this last section to be removed without being cut. Moreover, applying a demolding agent would not be necessary, because, after 24 hours, any possible shrinkage will facilitate the extraction of the test tube. Furthermore, the *MC* of the sample should be controlled, due the fact that it has a decisive influence on the variable *CS* [64,65]. Samples should therefore be cured in an environment with few temperature and relative humidity fluctuations (20ºC ± 2ºC and 65 ± 5%, respectively).

Figure 6. Types of cubic and prismatic test tubes. Source: the authors.

Similar to mechanical strength tests on concrete, it is necessary to wait 28 days, especially when it is stabilized with cement or lime. In order to get the same *MC* for all A samples, they were treated for 27 days under the same environmental conditions. Then, they were dried for 24 hours by a heater at 90 ºC until constant weight, because the moisture content may modify certain properties and measures (such as the ultrasonic pulse velocity [50]), together with its mechanical behavior. Special care has to be taken when applying a dry oven on non-stabilized samples, since water removal may influence on decreasing mechanical performance [20].

Table 6. Proposed quality control to rammed earth products during the construction work.

Sample Test	Information	Values	References		Frequency
Tests (Samples)					
Unconfined compression strength	Mechanical strength. *CS* (N/mm^2).	Variable depending on the reference. *CS* > 1–15	[61]	CO	2 A samples per controlled batch
Porosity and dry density	Quality. *P* (%). *D* (gr/cm3).	Soil variable. *P* = (30–40)% *D* = (1.5–2.8) (gr/cm^3)	[48]	CO	2 B samples per controlled batch
Ultrasonic pulse velocity	*UPV* (km/s) Quality estimation (compactness).	Highly variable. *UPV* = (1–3) Km/s (10% lime)	[49,50]	RE	2 A samples per controlled batch [2]
Rebound hammer	Surface hardness. Quality estimation. Rebound index (R).	Highly variable. *R* = 30–80 (Schmidt OS-120PT) (with 10% lime)	[49,53,61]	RE	2 A samples per controlled batch [2]
Wall Test	**Information**	**Values**	**References**		**Frequency**
Ultrasonic pulse velocity	UPV (km/s) Quality estimation (compactness).	Highly variable. *UPV* = (1–3)Km/s (10% lime)	[49,50]	OP	1 test [1] per week
Rebound hammer	Surface hardness. Quality estimation. Rebound index (R).	Highly variable. *R* = 30–80 (Schmidt OS-120PT) (10% lime)	[49,53,61]	OP	1 test [1] per week
Nuclear gauge	Quality estimation (compactness). Density and moisture content.	Compare with normal or modified Proctor. > 90–95% of Proctor density benchmark.	[66]	RE	1 test [1] per week

Notes: [1] Check finished elements whose corresponding mixes and samples have given mechanical results that may be rejected. [2] On same samples to be used for *CS* testing. CO: Compulsory; OP: Optional; RE: Recommended.

4.3. Testing of Rammed Earth Materials During the Construction Work

During the execution process, the quality control of the rammed earth materials has to be based on the lot size. Proposed tests in the literature and reference values are shown in Table 5.

Note the importance of controlling both the amount of water that is present during ramming and also the level of compaction that is achieved. Thus, periodic sampling of relative humidity of the dosage and soil stockpiling (see Table 5) are required in order to corroborate whether it is optimal for compaction. If this is not the case, then it is necessary to locate both the incorrect batch and mix.

The drop test is performed to assess qualitatively the variable *MC* of a soil, by evaluating the break in a soil sample after the impact on a hard and stable surface. It has been argued by certain authors that the accuracy is not enough to support decision making during the mixing of materials. Therefore, only tests such as [62] can provide quantitative and reliable values to accept a mixing process. Nevertheless, since this laboratory test is time consuming, the drop test may be used as a complementary procedure to facilitate the assessment of the variable *OMC* of a mixing soil, as long as it is supported by any other quantitative determination.

Construction materials related to rammed earth are evaluated before the execution process and also during the works, whenever any change in the supply implies an alteration of the parameters to be controlled. Since the water content of the stored soil may vary, the water added during the mixing should be adjusted to achieve the values of the variable *OMC* that are established in Table 3. It is hence necessary to control the variable *MC* at least for each mix batch under statistical supervision according to the number *n* that was discussed in Section 3. Other tests, such as the *GSD* or the Proctor test, only have to be performed when the soil changes.

The rejection or acceptance values for the most widely reported tests vary within similar ranges depending on which reference in the literature is consulted, but the most common are suggested in the tables of the current paper.

4.4. Testing of Rammed Earth Products During the Construction Work

During the construction work, all the variables *CS*, *D*, *P*, *UPV* and *R* can be determined (see Table 6) by means of samples, prepared by following all the indications in Section 4.2, and using similar means from those used on the worksite. Control frequencies shown in Tables 5 and 6 are based on the previously mentioned statistical representative sampling, by which at least 36 mixes per lot should be controlled, as long as the production and mixing conditions are as specified in Section 3. It is also considered both a production of 1.6 hours/m^3 of rammed earth wall and a normal level control of the work, which requires practitioners to have knowledge and adequate practice with these construction techniques. Thus, if the initial assumptions are technically less reliable, then it would be necessary to adjust the defined control lot size and sampling frequency. In this regard, those tests described for cubic samples (Table 6) should be performed, although a higher control frequency would be proposed for a more intense control level.

Complementary tests may be used on executed walls either when there are reasonable doubts about whether the rammed earth wall has not been correctly executed, or in order to verify the compliance of certain problematic characteristic values derived from mechanical testing of the samples made on site. In this regard, the nuclear gauge technique, which is widely used in pavement compaction, determines both the *D* and the relative humidity of a compacted layer [66] in a fast and agile manner. Given the reduced dimensions of some of these devices, they can be placed inside the formwork to take readings on just executed layers (see Figure 7a). This is a fast and relatively inexpensive technique, even if an accredited company is required for the specialized equipment.

Figure 7. In situ testing of the density and water content by means of a nuclear gauge (**a**). Extraction of a cored sample from a rammed earth wall (**b**). Source: the authors.

Cored samples can be taken directly from the rammed earth wall (Figure 7b). This technique has been used widely in cases dealing with concrete structures in order to develop complementary tests. For rammed earth walls, certain aspects must be taken into account, as discussed by Ciancio and Gibbings [46]. Thus, for example, cored samples tend to have less *CS* than molded ones, probably due to the damage that is generated during the drilling.

5. Discussion and Conclusions

In addition to the fact that there are few regulations on building rammed earth walls, there is no consensus on this technique, but a wide variability of proposed values due to the large number of variables related to earthen construction. All these aspects make the standardization and regulation of this building technique more complex. Even in the majority of references in the literature that propose tests or reference values, the procedures for their verification on site are scarce and not very precise. Due to this fact, this paper has introduced a procedure to control the quality of a rammed earth based on a statistical approach of the mechanical strength. To this end, a distinction is made between tests on both the material and the product, either in the form of samples (before and during the execution on site) or by means of on-site tests made on the worksite. Non-destructive tests (ultrasound and surface hardness), which are still rarely used on rammed earth, are considered as a possible source of additional information. Furthermore, the importance of compaction control by means of the determination of the *MMC* is stressed, whether by means of classic analytical techniques in the laboratory or by the application of technical means on site.

In any case, this is considered to be a preliminary proposal, because, in order to establish an equivalence with the most developed and contrasted control procedures for materials such as concrete, further work is still required. However, it is essential to understand that, given the variability of earthen materials, it is not easy to approach the design of a procedure to control the quality of rammed earth. Therefore, in order to avoid excessive restrictions that limit its application and undermine precisely one of its advantages, the proposed indications must be sufficiently flexible to enable the use of soils and other suitable materials from very diverse origins.

Some recommendations to carry out a quality control:

- The lot acceptance criterion is mainly based on the evaluation of the random variable *CS*. If the evaluated lot shows mechanical strength below the established threshold, then it is rejected and it is necessary to locate the deficient mix, either because of excessive mixing moisture, inefficient compacting energy or some hidden defect in the involved materials. In such cases a second round of tests based either on complementary tests or cored samples would need to be developed in order to recheck the parameters or to undertake further assessments.

- The current proposal is designed for a productivity of the rammed earth wall execution that is based on the capacity of the selected mixing system. If the performance of the equipment varied, then it would be necessary to adjust the number of batches so that the result (n) remains statistically representative of the total population (N). Equation (2) determines n as a function of N and other statistical parameters, namely σ, $Z_{\alpha/2}$, and e. The values used in Section 3 for these parameters may be valid for a typical sample production based mainly on the control of compaction energy and *MMC*.
- Taking the defined lot size as a reference, it is possible to adapt the sampling frequency according to the conditions of each site. Thus, different factors such as the construction company expertise, its workforce, the quality of both the materials involved and their stockpiling, the technical execution (either manual or mechanical) and the related auxiliary equipment, and formwork system, are indicators to establish different guarantees for a final quality of execution and, therefore, to make more or less restrictive decisions regarding quality control.
- The mixing method, in terms of technical system and volume capacity, may involve substantial differences in relation to the total volume of rammed earth wall that is required to be executed. As a consequence, for a considerable volume of rammed earth wall, if an adequate mixing system is not used to guarantee homogeneity, or if the volume of each mix is very small ($V_{LMS} < 250$ liters) compared with the total volume to be executed, then the control should be more restrictive and, hence, an increase in the sampling frequency could be considered.
- Concerning the compaction method, as has already been suggested in the literature, samples have to be as similar as possible to the executed wall. To this end, the materials involved in the control should be directly obtained from the same batch on the site and, whenever it is possible, samples should be made by the same workers. Furthermore, as the energy used in the compaction must be constant, the one involved in the Proctor test is taken as a reference. In order to reach this benchmark, an equation has been proposed to determine the number of strokes (s) according to the weight of the rammer and its fall height. The specific energy of the normal Proctor test (e_{OMC}) is equivalent to a manual or mechanical compaction using an energy per stroke of about 1 to 3.5 joules per stroke. For mechanical compactions, the equations suggested by Ciancio, Jaquin, and Walker [20] can be used to establish the compaction time according to the energy per stroke of the involved equipment.
- It is recommended to use cubic samples rather than cylindrical, since the former facilitate the use of non-destructive tests, such as the rebound hammer and the ultrasound pulse velocity. The size of samples is important, because every dimension that is smaller than three times the maximum aggregate size may give rise to unrepresentative samples. Moreover, an excessively small sample size in relation to the compaction energy may result in excessive confinement. To avoid the latter during the compaction process, the dimension of the rammer head should not be larger than the half of the edge of the cubic sample. It has been proven that the use of cubic samples with a cross section of 15 cm x 15 cm and square-head rammers of 7.5 cm give rise to suitable samples. The size of such rammers is similar to those pneumatic versions that are usually involved on site.
- A mixing moisture control is necessary to assess uniform mix and also to get the expected densities to be achieved for the established compaction energy. As the volume of kneading is usually reduced in comparison with the volume to be executed, a large number of mixes will be generated, of which a number per established batch will be statistically controlled. It is recommended to take at least three soil samples before and after the mixing in order to verify not only whether the optimum *MMC* has been reached, but also to establish the origin of the deviations and to evaluate possible solutions.

The statistical analysis of some other variables related to rammed earth construction, such as those related to durability (erosion test, shrinkage test, or wet/dry appraisal test) have not been considered in this research and are proposed as further work. This will be the concern of our future work.

Author Contributions: Conceptualization, J.C. and J.J.M.-d.-R.; methodology, J.C. and J.J.M.-d.-R.; formal analysis, J.C. and J.J.M.-d.-R.; investigation, J.C. and J.J.M.-d.-R.; data curation, J.C., J.J.M.-d.-R. and R.M.F.; writing—original draft preparation, J.C., R.M.F., and C.R.-B.; writing—review and editing, J.C., R.M.F., and C.R.-B.; visualization, J.J.M.-d.-R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors want to express their gratitude to the anonymous referees for the comprehensive reading of the paper and their pertinent comments and suggestions, which helped improve the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Glossary

σ	Standard deviation
CS	Unconfined compression strength
D	Dry density
e	Acceptable limit of the sampling error
e_s	Specific compaction energy
e_{OMC}	Specific compaction energy of the standard Proctor test
E_r	Energy generated by the fall of a rammer
g	Gravity acceleration value
GSD	Grain size distribution
h	Free-fall height of the rammer
MC	Moisture content
MMC	Molding moisture content
n	Number of controlled batches
N	Total number of batches
OMC	Optimum moisture content
P	Porosity
R	Rebound index
s	Number of strokes required to achieve the reference compaction energy
UPV	Ultrasound pulse velocity
V_{CMS}	Usable volume of the mixers in terms of the compacted volume of soil
V_{LMS}	Usable volume of the mixers in terms of the loose volume of soil
V_L	Volume of a layer
W	Weight of the rammer
$Z_{\alpha/2}$	Critical value depending on the confidence level
CO	Compulsory tests
OP	Optional test
RE	Recommended test

References

1. Fernandes, J.; Peixoto, M.; Mateus, R.; Gervásio, H. Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks. *J. Clean. Prod.* **2019**, *241*, 118286. [CrossRef]
2. Serrano, S.; Barreneche, C.; Rincón, L.; Boer, D.; Cabeza, L.F. Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA. *Constr. Build. Mater.* **2013**, *47*, 872–878. [CrossRef]
3. Arrigoni, A.; Beckett, C.; Ciancio, D.; Dotelli, G. Life cycle analysis of environmental impact vs. durability of stabilised rammed earth. *Constr. Build. Mater.* **2017**, *142*, 128–136. [CrossRef]
4. NZS 4298. *Materials and Workmanship for Earth Buildings*; Standards New Zealand: Wellington, New Zealand, 1998.

5. NMAC. *New Mexico Administrative Codes New Mexico 14.7.4. 2003. Earthen Building Materials Code*; Construction Industries Division of the Regulation and Licensing Department: Santa Fé, NM, USA, 2003; pp. 1–27.
6. SADCSTAN. *Rammed Earth Structures*; Code of Practice THC 03. SADCSTAN TC 1/SC 5/CD SAZS 724; African Organisation for Standardisation: Harare, Zimbabwe, 2014.
7. IS 2110. *Code of Practice for in-situ Construction of Walls, in Buildings with Soil-Cement*; Indian Standard; BIS. Bureau of Indian Standards: New Delhi, India, 1980.
8. Volhard, F.; Röhlen, U. *Lehmbau Regeln (Dachverband Lehm e.V)*, 3rd ed.; Springer Vieweg Verlag: Wiesbaden, Germany, 2009; ISBN 978-3-8348-0189-0.
9. Walker, P.; Keable, R.; Martin, J.; Maniatidis, V. *Rammed Earth. Design and Construction Guidelines*; BRE bookshop: Watford, UK, 2005; ISBN 1860817343.
10. Minke, G. *Manual de Construcción en Tierra: La Tierra Como Material de Construcción y su Aplicación en la Arquitectura Actual*; Fin de Siglo: Montevideo, Uruguay, 2005; ISBN 9974493471.
11. Doat, P.; Hays, A.; Houben, H.; Matuk, S.; Vitoux, F. *Building with Earth*; Editions Alternatives: Paris, France, 1991.
12. Font, F.; Hidalgo, P. *Arquitecturas de Tapia*; Colegio Oficial de Aparejadores y Arquitectos Técnicos de Castellón: Castellón, Spain, 2009; ISBN 978-84-613-3142-0.
13. Bauluz, G.; Bárcena, P. *Bases Para el Diseño y Construcción con Tapial*; Ministerio de Obras Públicas y Transportes Centro de Publicaciones: Madrid, Spain, 1992; ISBN 84-7433-839-5.
14. IETCC. *Obras de fábrica. P.I.E.T. Prescripciones del Instituto Eduardo Torroja de Ciencias de la Construcción*; Instituto Eduardo Torroja de la Construcción y del Cemento: Madrid, Spain, 1971; Volume 70.
15. Maniatidis, V.; Walker, P. *A Review of Rammed Earth Construction. DTi Partners in Innovation Project. "Developing Rammed Earth for UK Housing"*; Department of Architecture & Civil Engineering, University of Bath: Bath, UK, 2003.
16. UNE-103-500-94. *Geotechnic Compaction Test*; Standard Proctor; UNE-AENOR: Madrid, Spain, 1994.
17. Smith, J.; Augarde, C.E. Optimum water content tests for earthen construction materials. *Constr. Mater.* **2014**, *167*, 114–123. [CrossRef]
18. Ciancio, D.; Jaquin, P.; Walker, P. Advances on the assessment of soil suitability for rammed earth. *Constr. Build. Mater.* **2013**, *42*, 40–47. [CrossRef]
19. Hall, M.; Djerbib, Y. Rammed earth sample production: Context, recommendations and consistency. *Constr. Build. Mater.* **2004**, *18*, 281–286. [CrossRef]
20. Walker, P.; Stace, T. Properties of some cement stabilised compressed earth blocks and mortars. *Mater. Struct.* **1997**, *30*, 545–551. [CrossRef]
21. Rüsch, H.; Meseguer, A.G. Recommended principles for the control of quality and the judgement of acceptability of concrete. *Matériaux Et Constr.* **1975**, *8*, 387–403.
22. Rüsch, H.; Meseguer, A.G. Principios recomendados para el control de calidad del hormigón y criterios para su aceptación o rechazo. *Inf. De La Constr.* **1981**, *32*, 77–91. [CrossRef]
23. UNE 103-104-93. *Test for Plastic Limit of a Soil*; UNE-AENOR: Madrid, España, 1993.
24. UNE 103-103-94. *Determination of the Liquid Limit of a Soil by the Casagrande Apparatus Method*; UNE-AENOR: Madrid, España, 1994.
25. EHE-08. *Instrucción de hormigón estructural (EHE-08)*; Ministerio de Fomento, Secretaría General Técnica, Centro de Publicaciones: Madrid, Spain, 2009; ISBN 9788496698291.
26. Font, F.; Hidalgo, P. *El Tapial: Una Técnica Constructiva Milenaria*; Edición de los autores: Castellón, Spain, 1992.
27. López Osorio, J.M. The Nasrid ramparts of the Albaicín (Granada, Spain): An analysis of materials and building techniques. In *Rammed Earth Conservation—Mileto, Vegas & Cristini (eds)*; Rammed Earth Conservation—Mileto, Vegas & Cristini (eds); Taylor & Francis Group: London, UK, 2012; pp. 27–32. ISBN 978-0-415-62125-0.
28. Walker, P. *The Australian Earth Building Handbook*; Standards Australia International: Sydney, Australia, 2001; ISBN 9780733740008.
29. Junta de Andalucía. *Plan de Vivienda y Rehabilitación de Andalucía 2016–2020*; Consegería de Fomento y Vivienda. Junta de Andalucía: Sevilla, Spain, 2016.
30. Ryan, T.P. *Sample size Determination and Power*; Wiley series in probability and statistics; John Wiley & Sons: Hoboken, NJ, USA, 2013; ISBN 1-118-43924-4.
31. Martins Neves, C.M.; Faria, O.; Rotondaro, R.; Cevallos, P.; Hoffman, M. Selección de Suelos y Métodos de Control en la Construcción con Tierra. Available online: http://www.redproterra.org. (accessed on 4 January 2020).

32. UNE-EN 933-1. *Tests for Geometrical Properties of Aggregates—Part 1: Determination of Particle Size Distribution—Sieving Method*; UNE-AENOR: Madrid, Spain, 2012.
33. Houben, H.; Guillaud, H. *Earth Construction: A Comprehensive Guide*; Intermediate Technology Development Group: London, UK, 2008; ISBN 978 1 85339 193 4.
34. Schroeder, H. *Sustainable Building with Earth*; Springer: Cham, Switzerland, 2016; ISBN 9783319194905.
35. UNE 103102. Particle size analysis of a fine soil by sedimentation. In *Densimeter Method*; UNE-AENOR: Madrid, Spain, 1995.
36. Schulte, E.E.; Hopkins, B.G. Estimation of soil organic matter by weight loss-on-ignition. *Soil Org. Matter: Anal. Interpret.* **1996**, *46*, 21–31.
37. UNE 41410. Compressed earth blocks for walls and partitions. In *Definitions, Specifications and Test Methods*; UNE-AENOR: Madrid, Spain, 2008.
38. NZS 4297. Engineering Design of Earth Buildings. Available online: https://codehub.building.govt.nz/home/resources/42971998nzs/ (accessed on 4 January 2020).
39. Martín-del-Rio, J.J.; Flores-Alés, V.; Alejandre, F.J. New Method for Historic Rammed-earth Wall Characterization: The Almohade Ramparts of Malaga and Seville. *Stud. Conserv.* **2018**, *64*, 363–372. [CrossRef]
40. UNE 103-501-94. Geotechnic. In *Compactation Test*; Modified Proctor; UNE-AENOR: Madrid, Spain, 1994.
41. Ciancio, D.; Beckett, C.; Carraro, J.A.H. Optimum lime content identification for lime-stabilised rammed earth. *Constr. Build. Mater.* **2014**, *53*, 59–65. [CrossRef]
42. BS 1377-4. Methods of test for soils for civil engineering purposes. In *Compaction-Related Tests*; British Standards Institution: London, UK, 1990.
43. ASTM D698. *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort*; ASTM standards: West Conshohocken, PA, USA, 2012.
44. ASTM D1557. *Laboratory Compaction Characteristics of Soil Using Modified Effort*; ASTM standards: West Conshohocken, PA, USA, 1978.
45. Canivell, J.; Martin-del-Rio, J.J.; Alejandre, F.J.; García-Heras, J.; Jimenez-Aguilar, A. Considerations on the physical and mechanical properties of lime-stabilized rammed earth walls and their evaluation by ultrasonic pulse velocity testing. *Constr. Build. Mater.* **2018**, *191*, 826–836. [CrossRef]
46. Ciancio, D.; Gibbings, J. Experimental investigation on the compressive strength of cored and molded cement-stabilized rammed earth samples. *Constr. Build. Mater.* **2012**, *28*, 294–304. [CrossRef]
47. Graciani, A.; Martín-del-Río, J.J.; Mora, G.M.; Alejandre, F.J.; Canivell, J. Preliminary studies for intervention, interpretation and value enhancement of Tower of Don Fadrique (Albaida, Seville, Spain). In *Rammed Earth Conservation*; Rammed Earth Conservation; Taylor & Francis Group: London, UK, 2012; pp. 345–350. ISBN 978-0-415-62125-0.
48. UNE-EN-1936. *Natural Stone Test Methods—Determination of Real Density and Apparent Density, and of Total and Open Porosity*; UNE-AENOR: Madrid, Spain, 2007.
49. UNE-EN-13791. *Assessment of In-Situ Compressive Strength in Structures and Precast Concrete Components*; UNE-AENOR: Madrid, Spain, 2009.
50. UNE-EN-12504-4. *Testing Concrete*; Part 4: Determination of Ultrasonic Pulse Velocity; UNE-AENOR: Madrid, Spain, 2004.
51. UNE-EN 12504-2. *Testing Concrete in Structures*; Part 2: Non-destructive Testing. Determination of Rebound Number; UNE-AENOR: Madrid, Spain, 2013.
52. Bui, Q.B. Assessing the Rebound Hammer Test for Rammed Earth Material. *Sustainability* **2017**, *9*, 1904. [CrossRef]
53. Martín-del-Rio, J.J.; Canivell, J.; Falcón, R.M. 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.* **2020**, *242*, 118060. [CrossRef]
54. Bui, Q.B.; Morel, J.C. Assessing the anisotropy of rammed earth. *Constr. Build. Mater.* **2009**, *23*, 3005–3011. [CrossRef]
55. UNE-EN 12390-3. *Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens*; UNE-AENOR: Madrid, Spain, 2009.
56. UNE-EN-1015-11. *Methods of Test for Mortar for Masonry*; Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar; UNE-AENOR: Madrid, Spain, 2000.

57. Venkatarama Reddy, B.V.; Suresh, V.; Nanjunda Rao, K.S. Characteristic Compressive Strength of Cement-Stabilized Rammed Earth. *J. Mater. Civ. Eng.* **2017**, *29*, 4016203. [CrossRef]
58. Lombillo, I.; Villegas, L.; Fodde, E.; Thomas, C. In situ mechanical investigation of rammed earth: Calibration of minor destructive testing. *Constr. Build. Mater.* **2014**, *51*, 451–460. [CrossRef]
59. Tripura, D.D.; Singh, K.D. Behavior of cement-stabilized rammed earth circular column under axial loading. *Mater. Struct.* **2014**, *49*, 371–382. [CrossRef]
60. Bui, Q.B.; Morel, J.-C.; Hans, S.; Meunier, N. Compression behaviour of non-industrial materials in civil engineering by three scale experiments: The case of rammed earth. *Mater. Struct.* **2008**, *42*, 1101–1116. [CrossRef]
61. UNE-EN-12504-1. *Testing concrete in structures*; Part 1: Cored Specimens. Taking, Examining and Testing in Compression; UNE-AENOR: Madrid, Spain, 2009; p. 12.
62. UNE-EN-ISO-17892-1. *Geotechnical Investigation and Testing*; Laboratory Testing of Soil. Part 1: Determination of Water Content; UNE-AENOR: Madrid, Spain, 2015.
63. Cuchíi Burgos, A. La técnica tradicional del tapial. In Proceedings of the Actas del I Congreso Nacional de Historia de la Construcción, Madrid, Spain, 19–21 September 1996; edición a cargo de, Antonio de las Casas Gómez, Santiago Huerta Fernández, Enrique Rabasa Díaz; prólogo de, Ricardo Aroca Hernández-Ros, Antonio de las C. Instituto Juan de Herrera: Madrid, Spain, 1996; pp. 157–163.
64. Bui, Q.B.; Morel, J.C.; Hans, S.; Walker, P. Effect of moisture content on the mechanical characteristics of rammed earth. *Constr. Build. Mater.* **2014**, *54*, 163–169. [CrossRef]
65. Champiré, F.; Fabbri, A.; Morel, J.C.; Wong, H.; McGregor, F. Impact of relative humidity on the mechanical behavior of compacted earth as a building material. *Constr. Build. Mater.* **2016**, *110*, 70–78. [CrossRef]
66. UNE 103900. *In situ Determination of Density and Moisture Content of Soil and Granular Materials by Nuclear Methods: Low Depths*; UNE-AENOR: Madrid, Spain, 2013.