Hapres | Journal of Sustainability Research

sustainability.hapres.com

*Article*

# Towards the Recovery of Traditional Hot-Mixed Lime Techniques: Influence on the Construction Process and Structural Behaviour in Rammed Earth with Lime

**Camilla Mileto, Fernando Vegas, Alicia Hueto-Escobar *, Sergio Manzano-Fernández**

Architecture, Heritage and Management for Sustainable Development Research Centre (PEGASO), Universitat Politècnica de València, Valencia 46022, Spain; cami2@cpa.upv.es (CM); fvegas@cpa.upv.es (FV); sermanfe@upv.es (SMF)

* Correspondence: Alicia Hueto-Escobar, Email: alhuees@upv.es.

## ABSTRACT

Despite the widespread imposition of other types of industrial lime, the recovery of hot-mixed lime techniques is of interest both in its application in historic heritage interventions and its possible application in contemporary constructions. This article aims to contribute to this recovery through an initial phase of application to construction through the execution of reinforced rammed earth walls and test samples, providing conclusions on the practical implications of this traditional lime-slaking method. These test samples executions were then followed by a second phase of compression tests, incorporating further tests on samples of hot-mixed lime, air lime and hydraulic lime at different points in time. Thus, initial conclusions were established on the effect of hot-mixed lime on mechanical properties and their evolution over time compared to other industrial limes. Although the traditional method for slaking quicklime and its use in construction as hot-mixed lime is relatively straightforward, it is necessary to control its correct slaking and apply certain safety measures. The use of hot-mixed lime in reinforced rammed earth walls presents a slightly higher mean compressive strength than those which use slaked air lime and a mean compressive strength similar to that obtained with slaked hydraulic lime in initial phases, although it appears to be conditioned by the form of quicklime used. Based on these contributions the viable use of hot-mixed lime for construction or intervention in rammed earth walls is established and proves particularly advantageous in terms of structural advantages.

**KEYWORDS:** quicklime; lime slaking; compressive strength; comparative study

**Open Access**

Received: 17 January 2025
Accepted: 01 April 2025
Published: 14 April 2025



## INTRODUCTION

The use of lime as a construction material dates back to prehistoric times, when the technique for lime production appeared in Anatolia circa

15000 BC. Its first use in construction in the Mediterranean region was documented circa 10300–85000 BC, while in the Iberian Peninsula it appeared circa 7000 AC [1]. Lime is obtained from the calcination of limestone with a high content of calcium carbonate $CaCO_3$ in kilns reaching temperatures of around 900–1000 °C. Initially, this results in quicklime formed by calcium oxide CaO which is then hydrated and transformed into calcium hydroxide $Ca(OH)_2$ or slaked lime suitable for use in construction. Water is lost through evaporation once this lime comes into contact with the carbon dioxide of the atmosphere and a carbonation process begins through which calcium carbonate CaO is obtained, with the hardness and compressive strength of the product progressively increasing.

Although modern calcination and hydration processes are developed under controlled industrial conditions, certain aspects of the traditional process can be considered of great material and cultural relevance. In this regard, the presence of a number of local companies which continue to practise the calcination process using traditional kilns throughout Spain should be noted [2,3]. In terms of hydration processes, Spanish historic treatises describe multiple processes including the ordinary and spontaneous methods, as well as aspersion, immersion, and decanting [4–8]. From the 20th century the use of this last process became widespread as it enabled the slaking of large amounts of lime, benefiting construction on a larger scale [9]. As a result, currently industrially slaked lime is used primarily in construction, jeopardizing the continuity of traditional knowledge on quicklime hydration and transformation processes.

In this regard, numerous recent studies highlight how a large part of the earthen and lime mortars used in historic buildings within Europe were slaked and hot-mixed on site [10–18]. The use of this type of traditional process can mostly be identified by the presence within the mortar of calcrete or small jagged lime fragments containing particle remains that have been overcalcined, undercalcined or have not been hydrated [19]. This reference to the slaking of quicklime with the aggregates that are to be used in the execution of the desired mortar, putty or mix, makes it necessary, after slaking, to add the correct quantity of water depending on the element to be produced. The traditional lime-slaking method generally consisted in using aggregates to form a well-like structure and obtain the final amount of lime desired, pouring in the estimated amount of quicklime and water and using this aggregate to close or cover the well, forming a small mound (Figure 1) [20]. During this process, known in Spanish treatises as the ordinary method [8] or slaking by aspersion [7], the cracks forming on the surface are covered with sand in order to ensure suitable temperature and humidity conditions are maintained for correct hydration. In order to confirm whether quicklime has been correctly slaked, historic treatises suggest introducing a stick in the mound to check whether the entire length is covered by putty-like lime. However, the appearance of dry powdery points and the emission of vapours from the well in the small mound indicate that certain areas have not been slaked and that more water is required [6–8].

The form of lime that will be obtained following the quicklime slaking process is determined by water quantities. Broadly speaking, and always bearing in mind that the amount of water necessary for slaking depends on the characteristics of the lime itself, a homogeneous water-to-lime ratio is required in order to obtain dry-slaked lime. However, a slaked lime putty can be obtained with a water-to-lime ratio of 2:1 [21,22]. Several classic architectural treatises stress the need to add only the bare minimum of water for correct hydration, in order to prevent "drowning" [6–8].

**Figure 1.** Quicklime slaking process using the traditional method to prepare a mortar, part of the construction experiments carried out in this study.

In parallel, the studies developed on rammed earth walls in Spain have identified a number of traditional solutions combining earth and lime in different ways [23–25], including rammed earth with gypsum reinforcements, rammed earth with lime reinforcements, rammed earth with lime joints, etc. In the specific case of the rammed earth wall with gypsum reinforcements of the tower of Islamic origin in Bofilla, in the town of Bétera (Valencia, Spain), an earth to lime ratio of 9:1 was identified [26,27]. As this ratio falls within the values traditionally used for earthen mortars stabilized with hot-mixed lime [20,28] further research could be carried out on the possible correlation between the application of these mortars and the execution of reinforced rammed earth walls. Adding lime to an earthen mix results in clay clustering and initial hardening of the mass, while a reaction of the lime particles made up of compound silicates of calcium and aluminium increases both final strength and water resistance [29].

In recent decades, the use of lime in architecture has seen a significant resurgence, buoyed by its versatility, durability and sustainability. In addition to providing the necessary compatibility for architectural heritage interventions, these properties have also aided the application of lime in contemporary construction, prompting numerous studies [21,22,30]. Some of the most widely researched topics include chemical transformations, mechanical characteristics such as hydraulicity, permeability and insulation, and their evolution over time [31–38]. However, many of these studies focus mostly on air lime and hydraulic lime slaked using industrial methods, with few—if any—references to the potential implications of the use of hot-mixed lime or the traditional slaking process in the characteristics studied and in the workability or ease of execution of construction elements [22,28,39]. Equally, although the research addressing the process of traditional lime slaking and the use of hot-mixed techniques focuses primarily on mortar and rendering, no studies have examined the implications of its use or potential chemical or physical effects in the construction of rammed earth walls.

Similarly, the stabilization of earth through the addition of lime has been the subject of multiple studies in recent years, aiming to improve its mechanical strength, water resistance, and long-term durability [40–44]. Adding lime and the consequent hydration reaction increases the concentration of $Ca^{2+}$ and $OH^{-}$ ions, generating particle flocculation and raising the pH. This process facilitates the dissolution of silica and alumina from the minerals present in the soil, which react with calcium to form calcium silicate hydrates that enhance binding and increase mechanical strength [45]. Although industrial materials such as cement have become the most common stabilizer in rammed earth walls [40], some researches have also been conducted on stabilizing this construction technique with lime, focusing on the appropriate percentage and the resulting increase in mechanical strength [46–50]. Additionally, specific methods have been developed to restore rammed earth walls using sprayed earth stabilized with lime [51]. However, most of these studies focus only on industrially slaked limes, such as natural hydraulic lime or air lime.

Although advances have been made in the knowledge of lime as a material, they have generally focused on industrially slaked lime and, occasionally, on traditionally slaked and hot-mixed lime used in mortars and coatings. However, there are numerous indications that traditionally slaked and hot-mixed lime may have been frequently used as a stabiliser in the construction of rammed-earth walls. As traditional techniques are threatened by the dominance of industrial methods of production and construction, it is necessary to explore the possible structural and constructive implications of their use in order to promote the recovery of these methods. Therefore, it was decided to carry out an initial study on the implications of the use of hot-mixed lime in the construction process for reinforced rammed earth walls and the resulting mechanical characteristics. This first phase is part of a broader line of research which aims to advance knowledge of traditional earthen techniques, in particular, promoting the practical recovery of these materials through knowledge transfer in both restoration and the construction of new buildings.

In this regard, this study is the result of a collaboration between the research team and the company EMR Estudios y Métodos de la Restauración which, through its chair, aims to promote research on traditional materials and their direct application in construction and restoration interventions. The company Cales Pascual provided the necessary materials, specifically stone quicklime, powdered quicklime, powdered hydrated air lime and hydraulic lime NHL-3.5 (Figure 2).


**Figure 2.** Types of earth and lime used in the research: stone and powdered quicklime, hydraulic lime NHL-3.5 and powdered hydrated air lime.

## MATERIALS AND METHODS

Following an initial bibliographical review, the methodology proposed combines practical construction work with laboratory tests aiming to obtain conclusions on the implications of the use of hot-mixed lime in both the execution and mechanical characteristics of reinforced rammed earth walls. This research was conducted in collaboration with the specialist Nigel Copsey during the execution of practical work.

For the execution of this research, soil from a company located in Sagunto (Valencia) was used. Granulometric tests conducted following the UNE-EN ISO 17892-4:2019 standard [52] identified a fraction of fine gravel of 9.5%, an homogeneous fraction of sands of 55.6%, and a fine fraction of silt and clay at approximately 34.9% (Figure 3). Considering the European Soil Classification System of the ISO 14688-2:2018 [53], the soil can be classified as silty sand or clayey sand, pending the performance of plasticity tests. The same company provided fine sand and gravel, with an average size ranging from 0.02–0.5 mm and 2–12 mm respectively.

Another fundamental material in the research was quicklime, supplied by the company Cales Pascual S.L., located in Paterna (Valencia). According to the UNE-EN 459-1:2015 standard [54], the unslaked quicklime used is a high-purity calcium lime with a CaO content greater than 90% and an MgO content lower than 5%. Based on the technical data sheet, in the stone format the specific values are 95.90% and 0.84% and in the powder format 97% and 1%, with a loss on calcination of 2.42%. Also, the pH is 12.4 in saturated solution at 25 °C, a density of 940 g/L and a reactivity of 5 minutes with a maximum temperature of 70 °C. The hydrated aerial lime has a mean value of 93% $Ca(OH)_2$ and 0.45% MgO. As well as a presence of 1% $SiO_2$, 0.3% $Al_2O_3$, 0.2% $Fe_2O_3$, 0.004% MnO and 5.7% $CaCO_3$. The average pH value is 12.4 in saturated solution at 25 °C and a density of 2240 g/L. Lastly, the used hydraulic lime correspond to NHL-3.5 type, according to the compressive strength reached after 28 days, with 28.5% of free lime $Ca(OH)_2$ and 0.99% of $SO_3$.

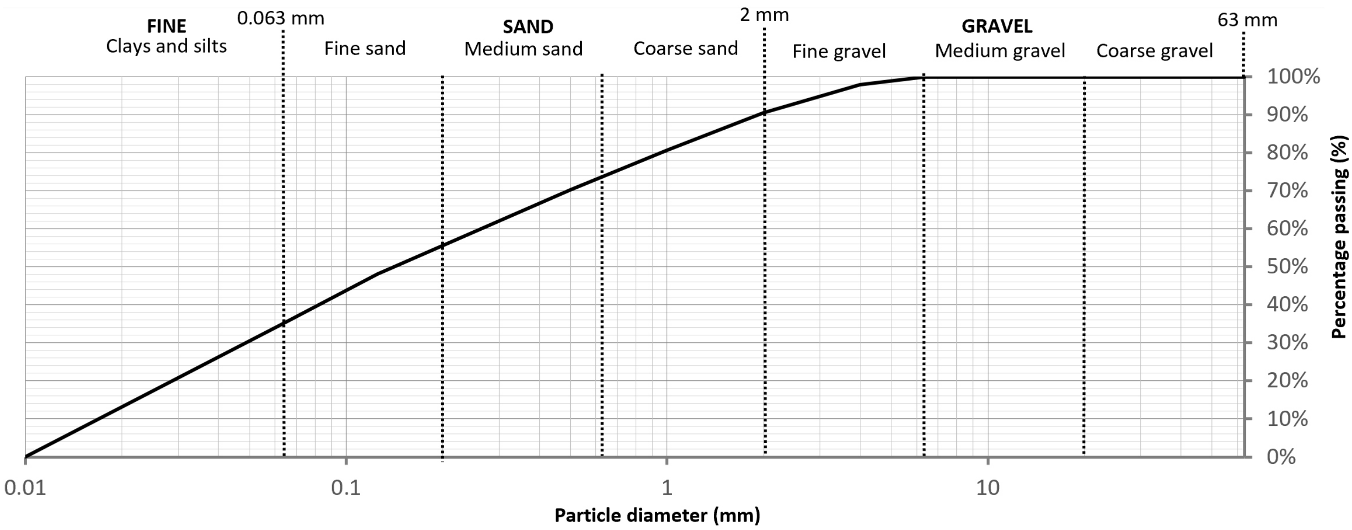


**Figure 3.** Particle size distribution of the soil.

### Experimentation on the Effect of Quicklime in the Construction Process

The first construction phase aims to identify conclusions on the traditional quicklime slaking process and its influence on the workability of the material when combined with earth. Therefore, this construction phase examined the slaking of quicklime following the traditional method, its execution in the construction of rammed earth walls reinforced with hot-mixed lime, and the execution of test samples for subsequent laboratory analysis. This in turn led to the analysis of practical aspects such as the timeframes needed to correctly slake and handle hot-mixed lime, the amount of water necessary to ensure suitable consistency, the compacting process, etc.

The chemical reaction observed in the lime during the traditional slaking process results in an increase in volume which must be considered when establishing the proportion and ratio of materials needed for the construction of the rammed walls and test samples of this study. According to estimations, when using a good quality or high purity lime volume is generally doubled [18,32]. Therefore, following hydration, the initial quantity established—a half part of quicklime—increased in volume and was considered a full part for the purposes of execution and calculation within the rest of the earth, aggregate and gravel mix. The parts of earth and aggregate added before executing the mound used for slaking also had to be considered.

Subsequently, two reinforced rammed earth walls—60 cm high, 84 cm long and 32 cm thick—were built in the facilities provided by Universitat Politècnica de València (Figure 4a and 4b). An initial wall T1 was built with a ratio of earth to hot-mixed lime of 18:1, the result of pulverizing quicklime in stone form and applying a traditional slaking process (Figure 5a) whereas a ratio of earth to hot-mixed lime of 9:1 was used to build a second wall T2, using stone quicklime for the lower half and powdered quicklime for the upper half (Figure 5b). The same type of mixture was used for both walls, made up of 4 parts earth with a high clay content, 2 parts sand, and 3 parts gravel.

These proportions were also used in other rammed earth walls previously built in the same location by the research team and incorporating the same types of earth, sand and gravel, and can therefore be incorporated into future studies on degradation processes. For the purposes of execution it was vital to incorporate a plinth in more resistant materials in order to mitigate any possible damage caused by damp due to capillarity. A protective element was also added to the upper section of the walls in order to control the effect of rainwater in degradation processes and develop the future research mentioned. This process was also used when experimenting with hot-mixed lime mortar for the execution of repairs on wall surfaces.

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


**Figure 4.** Execution process of rammed earth walls. (**a**) Assembly of formwork on pre-existing walls built on brick plinths. (**b**) Execution and tamping of rammed earth walls.

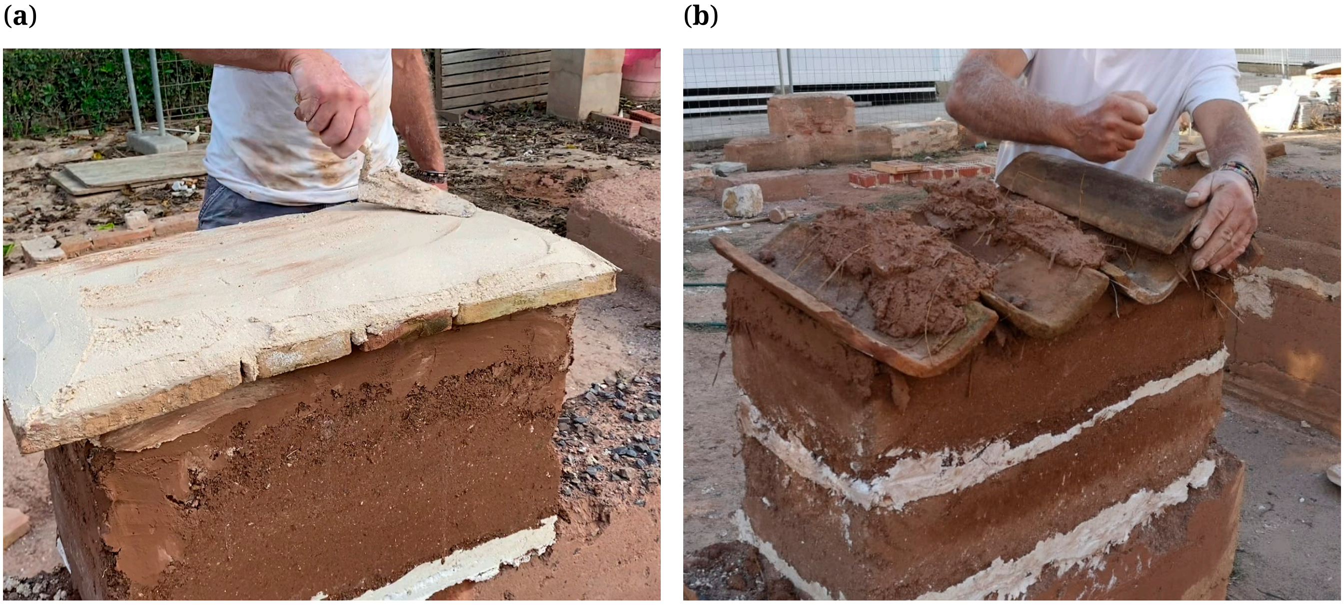

Figure 5. Execution process of protective elements on top of rammed earth walls. (**a**) Protective element with bricks and lime mortar on wall T1. (**b**) Protective element with curved tiles and earth mortar.

**Conformation of Samples for Structural Testing**

The execution of samples or test samples during the second phase aimed to elicit conclusions on the influence of the type and process of lime slaking in the structural resistance and evolution over time of reinforced rammed earth walls. The value of these tests lies in the comparison with compressive strengths obtained using other types of lime rather than in establishing specific compressive strengths, as this would have required further tests and stricter control of regulations. In this case the earthen mix used was the same as that used in the walls (4 parts earth, 2 parts sand, and 3 parts gravel), albeit with variations in the type and ratio of lime in the final mix. Each variation was tested, with a minimum of 5 samples, at 45, 90 and 180 days in order to examine increased resistance over time (Table 1).

**Table 1.** Description of the composition, ratio and time planning of the test samples used in compression tests.

| Identifier | Description | Earth-lime ratio | 45-day test | 90-day test | 180-day test |
|---|---|---|---|---|---|
| CV1 | Hot-mixed lime in stone form | 9:1 | 5 samples | 5 samples | 5 samples |
| CV2 | Hot-mixed lime in powder form | 9:1 | 5 samples | 5 samples | 5 samples |
| CV3 | Hot-mixed lime in stone form | 18:1 | 5 samples | 5 samples | 5 samples |
| CA1 | Hydrated air lime | 9:1 | 5 samples | 5 samples | 5 samples |
| CH1 | Hydraulic lime NHL-3.5 | 9:1 | 5 samples | 5 samples | 5 samples |

As there is no specific regulation for conducting structural tests on this type of construction [55–57], the recommendations from Rammed Earth Design and Construction Guidelines have been used as reference [58]. It was necessary to reduce the dimensions of test specimens established in the guidelines in order to adapt to the laboratory resources.

The test samples were executed using 10 × 10 × 10 cm moulds consisting of a horizontal base and four vertical sides anchored with screws that can be removed easily without damaging the pieces. While it is generally accepted that the shape and size of the samples can affect the mechanical properties obtained, the dimensions used in the present research are similar to those used in other studies [47,48,59]. In order to establish homogeneous execution conditions for all the test samples, it was vital to use the same heavy hammer and timber board for tamping, adding a specific mix amount with every layer and using the same number of tamping movements. Each mould was divided into 5 homogeneous layers, applying a total of 30 tamping movements per layer.

Therefore, the execution process for test samples consisted in the slaking of quicklime using the traditional procedure to obtain dry hot-mixed lime (Figure 6a), allowing enough time to ensure correct hydration (Figure 6b) and subsequently mixing it with the rest of earth, sand, and gravel once the slight drop in temperature allowed for safe working conditions with the material (Figure 6c). The time necessary for correct hydration of the lime depends on the chemical characteristics of the material. Based on the empirical knowledge of the artisan, it was considered that the lime hydration process was finished when superficial cracks stopped appearing in the pile and it stopped emitting heat. In the present research, the time range was between 30 and 45 minutes.

The weather conditions at the time may also have influenced this process. The open data provided by the Spanish State Meteorological Agency for the station located at the Universitat Politècnica de València recorded a daily average temperature of 23.1 ℃ and an average relative humidity of 68%, with no precipitation (Table 2).

**Table 2.** Climatic data at the time of samples execution, extracted from AEMET OpenData.

| Date | Average Temperature (°C) | Minimum Temperature (°C) | Maximum Temperature (°C) | Average Relative Humidity (%) | Minimum Relative Humidity (%) | Maximum Relative Humidity (%) |
|---|---|---|---|---|---|---|
| Day 1 | 24.6 | 20.5 | 28.6 | 74% | 48% | 90% |
| Day 2 | 21.8 | 19.3 | 24.4 | 89% | 87% | 90% |
| Day 3 | 23.7 | 19.6 | 27.8 | 57% | 45% | 91% |
| Day 4 | 23.1 | 18.8 | 27.4 | 57% | 44% | 74% |
| Day 5 | 20.4 | 17.5 | 23.2 | 62% | 53% | 74% |
| Average | 23.1 | 19.3 | 27.4 | 62% | 48% | 90% |

Moulds were then filled and compacted according to the conditions established (Figure 7a), on average waiting 4 hours before removing the test samples from the moulds (Figure 7b) and storing them in an interior space that could ensure homogeneous temperature and humidity conditions during the period leading up to the execution of tests.

Based on the data provided by the Universitat Politècnica de València for the months between December 2023 and April 2024, the average temperature of the storage space ranged between 18 and 22 ℃, with an ambient relative humidity of 55%–65%. These parameters are aligned with the ones established in the reference guidelines, which range from 15–20 ℃ and 40%–60% relative humidity [58].

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

**Figure 6.** Execution process of the used mix. (**a**) Mixing quicklime with water to begin the process. (**b**) Process for slaking lime during the time needed for the correct hydration to take place. (**c**) Adding the rest of the mix and water to ensure a suitable consistency.

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

**Figure 7.** Execution process of test samples. (**a**) Filling and compacting moulds. (**b**) Process for dismantling moulds after a prudential amount of time.

**Execution of Compression Tests**

The uniaxial compressive strength was determined by performing uniaxial compression tests by applying a homogeneously distributed load on the upper face of the sample until failure. These tests were carried out using an IBERTEST hydraulic press from the STIB series, with a maximum capacity of 400 kN, computerized measurement with WINTEST software, and adjustable compression plates with adaptors suited to the dimensions of the test samples studied (Figure 8). The test was programmed at a speed of 4 kg/s to adapt to the material types tested, aligned with the recommendation of the reference guidelines which establish a specimen stress of 0.2 N/mm$^2$ per minute or an equivalent speed of 3.40 kg/s for a surface of 100 × 100 mm$^2$ [58]. Given that rammed earth is an isotropic material [60] force was applied parallel to the layers in order to ensure direct contact between the press and the smoothed surface. After completing individual breakage tests each of the test samples was collected, stored and labelled for possible use in other laboratory tests.

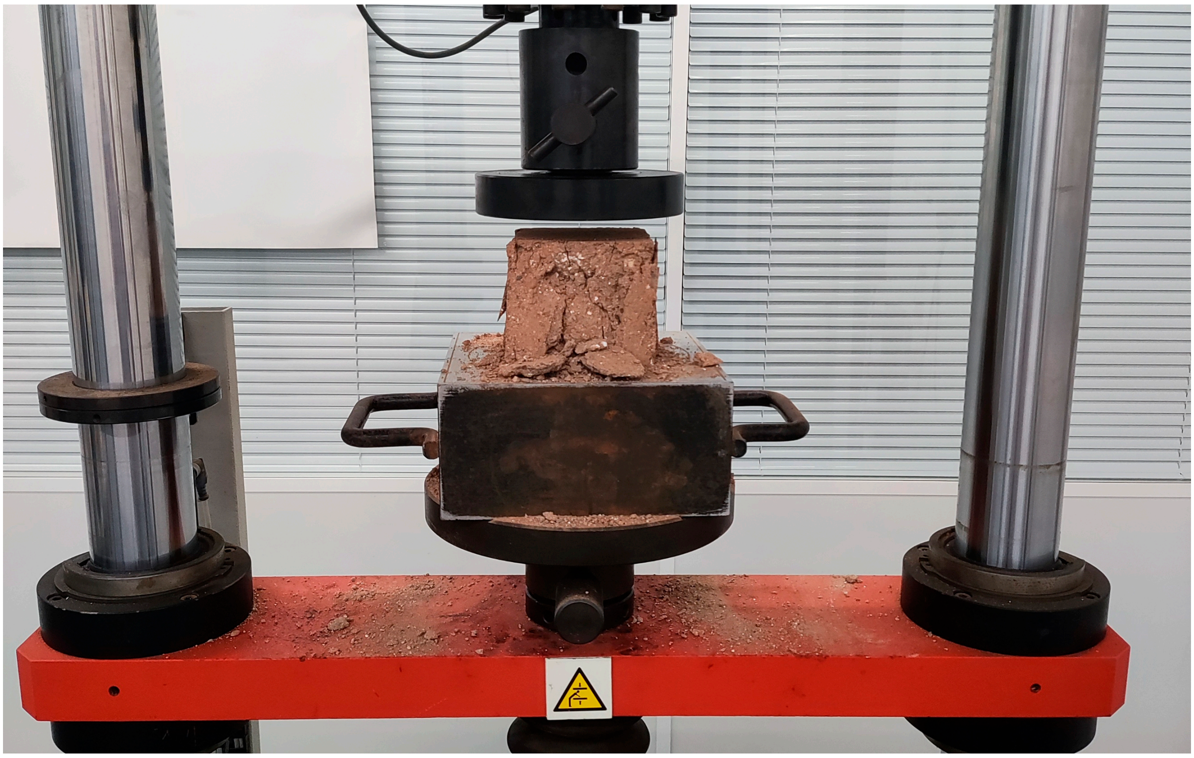

**Figure 8.** Compression tests using a hydraulic press at the Department of Architectural Constructions at Universitat Politècnica de Valencia.

In order to confirm the existence of atypical values, and given the small sample size, the results obtained were reviewed using Dixon's Q test. This method is based on the comparison of a $Q$ value and previously defined $Q_t$ critical values, with $Q_t$ = 0.710 established for a confidence level of 95%. The value $Q$ is defined as $Q = (X_a\text{-}X_b)/R$, where $X_a$ is the maximum or minimum value studied within the statistical sample, $X_b$ is the closest value to $X_a$, and $R$ is the difference between the maximum and minimum values of the complete statistical sample. If this critical value $Q_t$ is exceded, $X_a$ can be considered atypical and ruled out for safety reasons.

## RESULTS

### Influence on the Slaking Time and Required Water

The execution phase for rammed earth walls reinforced with hot-mixed lime and the test samples provided a series of observations and considerations on this execution process. Firstly, the traditional method used means that the chemical reaction occurring within a mound results in lower risk than other solutions referenced in historical treatises.

In terms of the timing for traditional slaking process for quicklime it was established that after a maximum of 10 minutes the appearance of surface cracks on the mound was halted, so that relative heat was preserved for a further 30 minutes. From that point on it was possible to directly touch the mound, although the slight presence of heat could still be detected. Finally, after mixing the mound with the rest of the earth, aggregate and gravel needed to execute the rammed earth and test samples, the complete mix stopped emitting heat after 45 minutes. In any case, it must be borne in mind that this time depends on the exact composition of the quicklime used and that suitable safety measures must be implemented to prevent personal harm, ensuring use of footwear, gloves and masks to prevent possible contact with vapours and other substances expelled [32,61]. It should be noted that—despite the relative increase in time entailed—prior planning can be used in this process to produce a sufficient amount of hot-mixed lime, improving both the degree of final hydration and its properties [14,15,35]. Furthermore, as this process only requires supervision during the initial phase to prevent the formation of cracks, other tasks can be performed while waiting for the temperature to drop.

A difference was detected in the amount of water needed to execute the test samples depending on the type of lime used. A suitable consistency was established for the earth and lime mix, respecting the general recommendation for the mix to preserve its form after pressure is applied without expelling excessive water or excessively staining the hands [62–64]. In this respect, the mix using hot-mixed lime required 3 parts water, while mixes with air lime and natural hydraulic lime required up to 4 parts water.

24 hours after execution, a considerable formation of calcrete was observed on wall T1 where stone quicklime with an earth to lime ratio of 18:1 had been used (Figure 9a and 9b). Despite the quicklime slaking process having been completed and the short amount of time between this and the execution, an ongoing chemical reaction in the material could be observed inside the wall. This expansive exothermic reaction encourages the nodules closest to the outer surface of the wall to increase in size, causing occasional small cracks called calcretes or caliches.

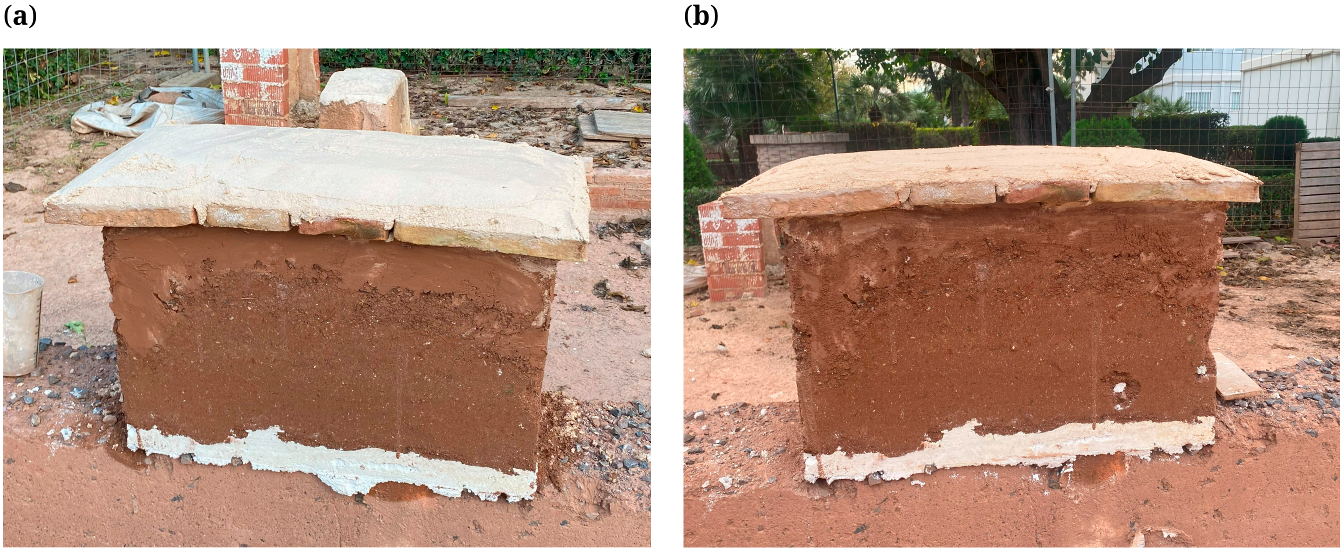

**Figure 9.** Appearance of a superficial calcrete or bulge on wall T1. (**a**) Wall surface on the day of the execution. (**b**) Wall surface the day after execution, showing a calcrete of considerable size.

**Uniaxial Compressive Strength of the Samples**

The results obtained in the compression tests (Table 3) were analysed beforehand to detect any atypical values due to the possible influence of individual test samples or the human factor during the execution process.

CV1 samples using stone quicklime reached a minimum compressive strength of 3.34 MPa after 45 days and a maximum value of 12.91 MPa after 180 days, while CV2 samples with the same earth to lime ratio but using pulverized quicklime respectively resulted in a minimum value of 2.38 MPa and a maximum value of 8.53MPa. When the lime ratio used was halved drastic reductions were observed in CV3 samples, with a minimum value of 0.62 MPa at 45 days and a maximum value of 5.82 MPa after 180 days. In the case of industrially slaked lime, the CA1 samples of hydrated air lime oscillated between 2.26 MPa at 45 days and 7.48 MPa at 180 days, logically increasing for CH1 samples of hydraulic lime and reaching 2.79 MPa and 13.24 MPa.

**Table 3.** Compressive strength values for all the test samples analysed, ruling out those identified as atypical according to Dixon's Q test.

| Sample description | Identifier | 45 days | 90 days | 180 days |
|---|---|---|---|---|
| **Sample type CV1**<br>Hot-mixed lime in stone form<br>Earth to lime ratio 9:1 | CV1 m1 | 3.68 MPa | 6.07 MPa | 10.98 MPa |
| | CV1 m2 | 5.83 MPa | 5.79 MPa | 7.61 MPa |
| | CV1 m3 | 6.08 MPa | 5.96 MPa | 5.39 MPa |
| | CV1 m4 | 5.00 MPa | 6.45 MPa | 5.28 MPa |
| | CV1 m5 | 3.34 MPa | 6.40 MPa | 12.91 MPa |

**Table 3.** *Cont.*

| Sample description | Identifier | 45 days | 90 days | 180 days |
|---|---|---|---|---|
| **Sample type CV2** | CV2 m1 | 5.30 MPa | 5.20 MPa | 6.91 MPa |
| Hot-mixed lime in powder form | CV2 m2 | 2.38 MPa | 2.56 MPa | 4.72 MPa |
| Earth to lime ratio 9:1 | CV2 m3 | 3.09 MPa | 5.69 MPa | 8.53 MPa |
| | CV2 m4 | 2.67 MPa | 5.59 MPa | 7.02 MPa |
| | CV2 m5 | 10.16 MPa * | 4.51 MPa | 5.95 MPa |
| **Sample type CV3** | CV3 m1 | 2.37 MPa | 3.63 MPa | 4.56 MPa |
| Hot-mixed lime in stone form | CV3 m2 | 2.30 MPa | 3.54 MPa | 3.22 MPa |
| Earth to lime ratio 18:1 | CV3 m3 | 0.62 MPa | 3.82 MPa | 4.54 MPa |
| | CV3 m4 | 4.41 MPa | 4.34 MPa | 5.69 MPa |
| | CV3 m5 | 3.48 MPa | 1.33 MPa * | 5.82 MPa |
| **Sample type CA1** | CA1 m1 | 3.09 MPa | 4.11 MPa | 7.35 MPa |
| Hydrated air lime | CA1 m2 | 2.26 MPa | 4.50 MPa | 6.72 MPa |
| Earth to lime ratio 9:1 | CA1 m3 | 3.43 MPa | 6.13 MPa | 7.48 MPa |
| | CA1 m4 | 3.84 MPa | 4.72 MPa | 6.11 MPa |
| | CA1 m5 | 5.88 MPa | 4.87 MPa | 6.85 MPa |
| **Sample type CH1** | CH1 m1 | 3.63 MPa | 4.95 MPa | 11.77 MPa |
| Hydraulic lime NHL-3.5 | CH1 m2 | 6.77 MPa | 9.01 MPa | 11.79 MPa |
| Earth to lime ratio 9:1 | CH1 m3 | 5.34 MPa | 8.09 MPa | 6.84 MPa |
| | CH1 m4 | 2.79 MPa | 4.35 MPa | 13.24 MPa |
| | CH1 m5 | 6.33 MPa | 4.28 MPa | 6.62 MPa |

* Atypical value ruled out by Dixon's Q test. The m in CV1 m1 means muestra.

After ruling out the atypical values from the sample, average compressive strength values were obtained for the five test sample types at 45, 90 and 180 days (Table 4), showing their progressive increase over time (Figure 10).

**Table 4.** Mean compressive strength values for the different samples obtained.

| Identifier | 45 days | 90 days | 180 days |
|---|---|---|---|
| CV1 | 4.79 MPa | 6.08 MPa | 8.43 MPa |
| CV2 | 3.36 MPa | 4.71 MPa | 6.63 MPa |
| CV3 | 2.64 MPa | 3.83 MPa | 4.76 MPa |
| CA1 | 3.70 MPa | 4.87 MPa | 6.90 MPa |
| CH1 | 4.97 MPa | 6.20 MPa | 10.05 MPa |

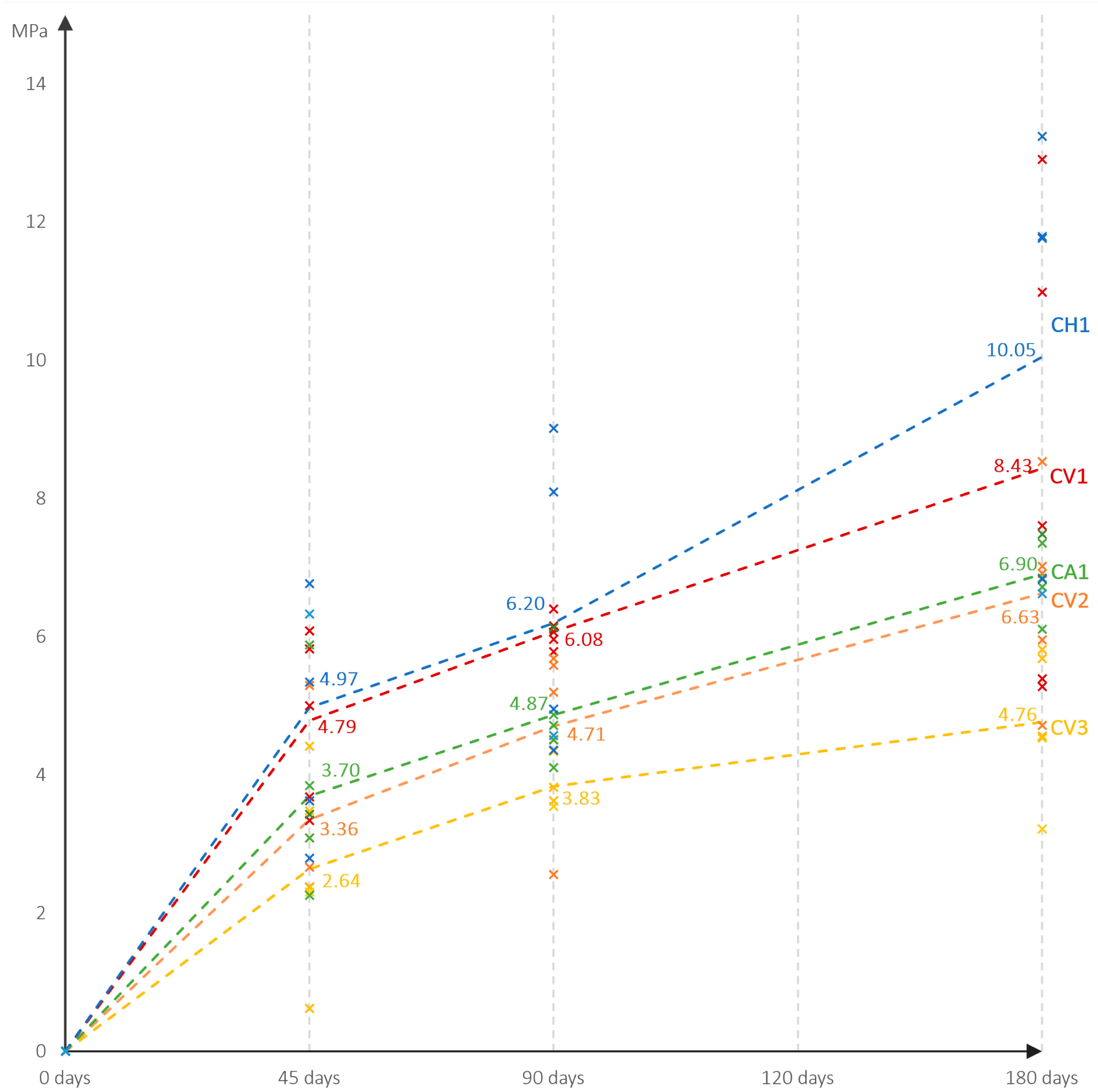


**Figure 10.** Evolution of mean compressive strength of test samples over time, showing the MPa values of each test sample type at 45, 90 and 180 days.

## DISCUSSION

The use of different types and ratios of lime in the rammed earth walls and test samples executed does not appear to modify aspects relating to the execution process, and similar time frames are required for the slaking, mixing and number of tamping movements. However, this appears to affect the amount of water needed for the execution of rammed earth walls and the development of some short-term lesions.

Firstly, equal amounts of water are needed for the complete execution cycle for hot-mixed techniques and the rest of solutions, as the excess required in order to ensure the necessary consistency for industrial lime is counterbalanced by that required for the in situ slaking process for hot-mix lime. It should be borne in mind that in order to obtain the suitable consistency for the execution of rammed earth walls with hot-mixed lime 3 parts were required, while in the case of industrial lime 4 parts water were required for every 9 parts earth and 1 part lime. However, as 1 part of water is necessary for traditionally slaking quicklime in the first case, the quantities are apparently equal. However, the cycle must also incorporate the industrial water consumption necessary for homogeneous slaking in factories, also adding to the difference in relation to traditional processes. Therefore, ultimately, the use of hot-mixed lime results in lower water consumption which could constitute an advantage in any settings or contexts where water is a limited resource, especially considering the large amounts of mix that are required for the construction of buildings or constructions with full-scale rammed earth walls. Although the savings may seem small, it is of particular interest considering that the construction industry consumes around 16% of total global water consumption [65].

As regards the development of short-term lesions, the general absence of calcrete in historic rammed earth walls documented by the research team suggests that, prior to the mixing of materials, hot-mixed lime was exhaustively sifted and screened. This observation is in keeping with the recommendations of historic treatises, where sifting recommendations proposed sieves made up of rectangular frames, placed at an angle with a wire or wooden mesh with 1–1.5 cm spaces [7]. However, recent studies highlight the advantage of the presence of small nodules of non-hydrated lime within the walls [66], as these enable possible cracks to be hydrated and filled in the event of the appearance of lesions. It would therefore be interesting for future research to analyse the optimum size of these nodules in order to achieve the reparative effect, without the formation of surface calcrete.

The specific advantages identified in this research support the sustainability of traditionally slaked and hot-mixed lime, although the feasibility of its widespread application is conditioned by certain factors. The use of traditionally slaked lime reduces the dependence of the construction sector on infrastructures or industrial facilities. In this regard, the use of industrially slaked lime requires the existence of factories and the subsequent transportation to construction sites, as well as the energy resources associated with industrial processes. The traditional method also involves some level of infrastructure, transportation, and energy consumption for quicklime production, although it is presumably lower. This is mainly because traditional and locally sourced materials are used for the construction of kilns, which are located near limestone outcrops and use firewood for combustion. In this sense, the feasibility of using traditionally slaked and hot-mixed lime undoubtedly requires the availability of quicklime and the preservation of the traditional knowledge associated with the slaking process. At the same time, its use is somewhat conditioned by the need to comply with regulations and quality control processes in construction projects, which are currently largely focused on industrialized materials and processes. While this poses a challenge for its widespread application in contemporary construction, it is an advantage for restoration purposes, as it allows adaptation to the specific conditions and requirements of each intervened element.

For this last aspect, it is undoubtedly important to determine the structural implications of using traditionally slaked and hot-mixed lime. The comparative analysis of the mean values of compressive strength in lime-stabilized wall samples is complex, due to the absence of uniform standards for the tests and the execution procedure that would allow an objective comparison of results [40]. In the absence of comparable studies for hot-mixed lime, it should be noted that the mean compressive strength values obtained for the samples with hydrated air lime and hydraulic lime NHL-3.5 are within the ranges established by other similar investigations. Recent investigations on earth elements stabilized with natural hydraulic lime show compressive strength values between 1.5 and 5 MPa at 28 days [47,49,67], a range within which the 4.97 MPa identified at 45 days in the present investigation falls (CH1). Similarly, the documented mean value of 3.70 MPa for the samples with hydrated air lime (CA1) falls within the range documented by other similar investigations for this type of lime, generally between 1 and 4.5 MPa [50,57,68].

However, it has been possible to obtain some initial conclusions on the implication of the use of hot lime on the mechanical behavior. In terms of the presentation of the quicklime used the notable increase in uniaxial compressive strength observed when using stone instead of powder should also be highlighted. The use of stone quicklime instead of powder improves the mean values of compressive strength by 42.5% at 45 days, 29.1% at 90 days, and 27.3% at 180 days (Table 5). The values obtained for stone quicklime are in keeping with the ranges established by other recent studies which highlight correlation between differences in relation to the pulverized form and ease of carbonation prior to execution and the subsequent lower percentage of final effective lime. Specifically, research focused on air lime and sand mortar samples with dimensions of 40 × 40 × 160 mm and different curing times, using hot lime in stone format resulted in an increase in average compressive strength compared to the powder format of 30.5% at 28 days and 36.9% at 90 days [36]. While this may be because quicklime stones are generally considered to be more reactive than powdered lime and therefore form stronger bonds, it may have implications in other physical properties such as porosity and shrinkage. It remains necessary to study the reasons for this increase in mechanical strength and to establish the precise point of balance between this improvement and other aspects that may be influenced.

**Table 5.** Improvement of compressive strength according to the format of hot-mixed lime: stone (CV1) and powder (CV2).

| **Identifier** | **45 days** | **90 days** | **180 days** |
|---|---|---|---|
| CV1 | 4.79 MPa | 6.08 MPa | 8.43 MPa |
| CV2 | 3.36 MPa | 4.71 MPa | 6.63 MPa |
| % increase | 42.5% | 29.1% | 27.3% |

The comparison of uniaxial compressive strength using different types of lime shows that hot-mixed lime in stone form yields slightly higher mean values than industrially slaked air lime using the same proportions. In the case of hot-mixed lime in stone form (CV1) the improvement in compressive strength mean values is 29.3% at 45 days, 24.9% at 90 days and 23.3% at 180 days compared to air lime (CA1) (Table 6). However, in powder form (CV2), these mean values are slightly lower, showing a reduction of 10.2%, 3.3% and 4.1% respectively (Table 7). While further research and development of laboratory studies to understand the influence of the form of quicklime used would be advisable, these values confirm a relative mechanical improvement derived from the use of hot-mixed lime over industrially slaked air lime.

**Table 6.** Improvement of compressive strength according to the type of lime: hot-mixed lime in stone format (CV1) and industrially slaked air lime (CA1).

| Identifier | 45 days | 90 days | 180 days |
|---|---|---|---|
| CV1 | 4.79 MPa | 6.08 MPa | 8.43 MPa |
| CA1 | 3.70 MPa | 4.87 MPa | 6.90 MPa |
| % increase | 29.3% | 24.9% | 23.3% |

**Table 7.** Improvement of compressive strength according to the type of lime: hot-mixed lime in powder format (CV2) and industrially slaked air lime (CA1).

| Identifier | 45 days | 90 days | 180 days |
|---|---|---|---|
| CV2 | 3.36 MPa | 4.71 MPa | 6.63 MPa |
| CA1 | 3.70 MPa | 4.87 MPa | 6.90 MPa |
| % increase | −10.3% | −3.3% | −4.1% |

**Table 8.** Improvement of compressive strength according to the type of lime: hot-mixed lime in powder format (CV1) and industrially slaked hydraulic lime (CH1).

| Identifier | 45 days | 90 days | 180 days |
|---|---|---|---|
| CV1 | 4.79 MPa | 6.08 MPa | 8.43 MPa |
| CH1 | 4.97 MPa | 6.20 MPa | 10.05 MPa |
| % increase | −3.3% | −2.1% | −19.2% |

Furthermore, it should be stressed that the hydraulic lime test samples executed show smaller increases than the mean values initially obtained with hot-mixed lime in stone form. They show an increase of 3.3% at 45 days and 2.1% at 90 days, reaching 19.2% at 180 days (Table 8). This is linked to the combined presence—within the hydraulic lime used—of air lime compounds which set upon initial contact with the atmosphere and other hydraulic lime compounds which continue to set inside the test samples, increasing their final compressive strength [69,70].

## CONCLUSIONS

The research carried out has concluded the initial viability of the use of hot-mixed lime, as once the slaking process has been completed and a prudential length of time has passed, the use of lime is equivalent to that of other types of industrially slaked lime. In this regard, it is worth highlighting the potential importance of correctly executed slaking process in the good behaviour of the material, especially when the amount of water added for slaking is controlled while also ensuring a suitable temperature is conserved throughout the process and the mix is correctly screened to prevent the appearance of calcretes. In addition, the results suggest that hot-mixed lime provides a more sustainable approach to rammed-earth wall construction, as it consumes less water compared to industrial lime. This characteristic aligns with the increasing need for environmentally friendly construction techniques, especially in regions where water scarcity is an issue.

In structural terms, compression test results show that the use of hot-mixed lime results in increased resistance in relation to those obtained with industrially slaked air lime, especially when using quicklime in stone form. Furthermore, the values obtained with hot-mixed lime in stone form are slightly lower than those obtained with hydraulic lime. The better performance of hot-mixed lime in stone powder could be related to the presence of nodules of unslaked lime. This may contribute to improved long-term durability, reducing the need for maintenance and increasing the service life of these structures. However, the major variations in resistance observed in the use of quicklime in stone and powder form should also be further explored in order to identify the causes and determine the degree of influence. Further studies should investigate the impact of the lime format, nodule size and distribution in the mechanical performance and the long-term durability. It is also essential to explore the influence of different curing conditions and environmental factors on the structural evolution of hot-mixed lime, as these parameters could significantly affect mechanical performance over time.

Considering the above, it can be concluded that the application of hot-mixed lime in the construction of rammed earth walls provides interesting advantages over the use of industrial air lime, guaranteeing a slight increase in compressive strength and lower water consumption, without excessively complicating the execution process as long as safety measures and correct slaking are guaranteed. The present research contributes to the broader field of sustainable construction by demonstrating how traditional materials and techniques may be effectively reintroduced into contemporary building practices without compromising the mechanical behaviour or the execution process. However, future research should focus on optimizing slaking and mixing techniques to ensure consistent mechanical performance and minimize variability, as well as studying the influence of hot-mixed lime use on other mechanical parameters. Finally, establishing standardized testing protocols for hot-mixed lime applications in structural elements would be crucial for ensuring broader acceptance and implementation in both heritage conservation and modern construction.

## DATA AVAILABILITY

The dataset of the study is available from the authors upon reasonable request.

## AUTHOR CONTRIBUTIONS

Conceptualization, CM, FV, AHE, and SMF; Methodology, AHE and SMF; Software, AHE; Validation, AHE and SMF; Formal Analysis, AHE and SMF; Investigation, AHE and SMF; Resources, CM and FV; Data Curation, AHE and SMF; Writing—Original Draft Preparation, AHE and SMF; Writing—Review & Editing, CM, FV, AHE, and SMF; Visualization, AHE and SMF; Supervision, CM and FV; Project Administration, CM and FV; Funding Acquisition, CM and FV.

## CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

## FUNDING

This work was funded by Cátedra EMR-CPA. This research is included in the research project "Earth4Future: Sustainable reuse of earthen architecture and its lessons for contemporary architecture" (Reference PID2022-139154OB-I00), funded by the Spanish Ministry of Science, Innovation and University and in the research project "Re-Habitat: Restauración y rehabilitación sostenible de viviendas tradicionales en contextos históricos" (Reference CIAICO/2022/035) funded by the Regional Ministry for Innovation, Universities, Science and Digital Society of the Generalitat Valenciana.

## ACKNOWLEDGMENTS

The authors wish to thank the EMR-CPA Chair for the support provided, the assistance from members of staff and the availability of the Laboratory of the Department of Architectural Construction of the Escuela Técnica Superior de Arquitectura at the Universitat Politècnica de València, the experience and knowledge transmitted by the specialist Nigel Copsey and the material provided by the company Cales Pascual.

The authors also wish to thank Salvador Tomás Márquez for his participation in the initial lime selection process and the management of supplies.

## REFERENCES

1. Pastor Quiles M. La construcción con tierra en la Prehistoria reciente del Levante meridional de la península ibérica: materiales, técnicas y procesos

constructivos [Earth construction in the recent prehistory of the southern Levant of the Iberian Peninsula: materials, techniques and construction processes] [dissertation]. Alicante (Spain): Universidad de Alicante; 2019. Spanish.
2. Mileto C, Vegas López-Manzanares F, García Saéz MS, Tomás Márquez S, García Hermida A. Maestros de la Cal [Masters of Lime]. London (UK): INTBAU; 2018. Spainish.
3. Mileto C, Vegas F, Cristini V. Documentación e Investigación para el conocimiento de la situación de los sistemas tradicionales de la construcción, así como de la extracción, utilización y puesta en obra de los materiales tradicionales en España [Documentation and research to understand the status of traditional construction systems, as well as the extraction, use, and implementation of traditional materials in Spain]. Valencia (Spain); IPCE, Ministerio de Educación, Cultural y Deporte; 2014. Spanish.
4. Bails B. Elementos de matemática [Elements of mathematics]. 2nd ed. Madrid (Spain): Imprenta de la Viuda de D. Joaquín Ibarra; 1796. Spanish.
5. Ger y Lobez F. Tratado de Construcción Civil [Civil Construction Treaty]. Badajoz (Spain): La Minerva Extremeña; 1898. Spanish.
6. Marcos y Bausa R. Manual del Albañil [Bricklayer's Manual]. 3rd ed. Madrid (Spain): Tipografía de Gregorio Estrada; 1879. Spanish.
7. Rebolledo JA. Manual del Constructor conteniendo los conocimientos indispensables que deben poseer los encargados de dirigir o ejecutar las obras públicas o particulares en los casos de más frecuente aplicación [Builder's Manual containing the essential knowledge that those in charge of directing or executing public or private works must possess in the most frequently applied cases]. 4th ed. Madrid (Spain): Sáenz de Jubera Hermanos; 1893. Spanish.
8. Espinosa PC. Manual de Construcciones de Albañilería [Masonry Construction Manual]. Madrid (Spain): Imprenta a cargo de Severiano Baz; 1859. Spanish.
9. Lima J. Argamassas tradicionais de cal aérea: aspectos da sua composição e desempenho nos sistemas construtivos tradicionais [Traditional aerial lime mortars: aspects of their composition and performance in traditional construction systems]. In: Conceição L, editor. Novos Dispersos de Arquitectura [New Architecture Dispersals]. Lisboa (Portugal): ISMAT—Instituto superior Manuel Teixeira Gomes; 2014. p. 1-7. Spanish.
10. Forster A. Hot-lime mortars: A current perspective. J Architect Conserv. 2004;10(3):7-27.
11. Henry A. Hot-mixed Mortar. Mortars for conservation: current perspectives & recent research. London (UK): Historic England; 2017.
12. Holmes S. Hot Limes in a cold climate. J Build Limes Forum. 1993;1(2):5-19.
13. Lynch G. The Myth in the Mix: The 1:3 ratio of lime to sand. Available from: https://www.buildingconservation.com/articles/mythmix/mythmix.htm. Accessed on 10 Dec 2024.
14. Pavia S, Veiga R, Hughes J, Pesce G, Valek J, Alvarez JI, et al. RILEM TC 277-LHS report: How hot are hot-lime-mixed mortars? A review. Mater Struct. 2023;56(4):87.

15. Pesce C, Godina MC, Henry A, Pesce G. Towards a better understanding of hot-mixed mortars for the conservation of historic buildings: the role of water temperature and steam during lime slaking. Heritage Sci. 2021;9(72):1-18.
16. Snow JH. Hot-mixed Lime Mortars. 2nd ed. Edinburgh (Scotland): Historic Environment Scotland; 2016.
17. Copsey N. A critical review of historic literature concerning traditional lime and earth-lime mortars [dissertation]. York (UK): University of York; 2019.
18. Copsey N. Hot Mixed Limes and Traditional Mortars: a practical guide to their use in conservation and repair. Ramsbury (UK): Crowood Press; 2019.
19. Frew C, McElveen I, Revie W, McAfee P, Connolly J, Howard R, et al. HLM Project: Technology Transfer and Applied Research (Phase I). Dublin (Ireland): The Building Limes Forum Ireland; 2014.
20. Copsey N. Hiding in plain sight: hot mixed lime mortars. Loggia Arquit Restau. 2016;29:118-31.
21. Sandström Malinowski E. Historic Mortars Revived. In: Groot C, editor. Workshop Repair Mortars for Historic Masonry. Marne-la-Vallée (France): RILEM Publications SARL; 2009. p. 328-38.
22. Sandström Malinowski E, Hansen TS. Hot Lime Mortar in Conservation—Repair and Replastering of the Façades of Läckö Castle. J Architect Conserv. 2011;17:95-118.
23. Font F, Hidalgo P. Arquitecturas de tapia [Tapia architectures]. Castellón (Spain): Colegio Oficial de Aparejadores y Arquitectos Técnicos de Castellón; 2009. Spanish.
24. López Martínez FJ. Tapias y tapiales [Walls and rammed earth]. Loggia Arquit Restau. 1999;8:74-89.
25. Mileto C, Vegas F. La restauración de la tapia en la Península Ibérica: Criterios, técnicas, resultados y perspectivas [Restoration of the wall in the Iberian Peninsula: Criteria, techniques, results and perspectives]. Valencia (Spain): Argumentum, TC Cuadernos; 2014. Spanish.
26. Mileto C, Vegas F. La restauración de la torre de la alquería de Bofilla en Bétera (Valencia) [The restoration of the tower of the Bofilla farmhouse in Bétera (Valencia)]. In: Gordillo D, editor. Fortificaciones. Intervenciones en el patrimonio defensivo [Fortifications. Interventions in defensive heritage]. Madrid (Spain): Ministerio de Educación, Cultura y Deporte, Col·legi d'Arquitectes de Catalunya, Agrupacio d'Arquitectes per a la defensa i la intervenció en el patrimonio arquitectónic; 2011. p. 95-102. Spanish.
27. Mileto C, Vegas F, López JM. Criterios y técnicas de intervención en tapia. La restauración de la torre Bofilla de Bétera (Valencia) [Criteria and techniques for wall interventions. The restoration of the Bofilla Tower in Bétera (Valencia)]. Inf Constr. 2011;63(523):81-96. Spanish.
28. Copsey N, Gourley B. Hot-mixed lime mortars. J Build Limes Forum. 2015;22:70–6.
29. Henry A, McCaig I, Willett C, Godfraind S, Stewart J. Earth, Brick & Terracotta. London (UK): Historic England, Ashgate Publishing Limited; 2015.

30. Hughes JJ, Valek J. Mortars in historic buildings: A review of the conservation, technical and scientific literature. Edinburgh (Scotland): Historic Scotland; 2003.
31. Banfill PFG, Forster AM. A relationship between hydraulicity and permeability of hydraulic lime. In: Bartos P, Groot C, Hughes JJ, editors. International RILEM Workshop on Historic Mortars: Characteristics and Tests. Marne-la-Vallée (France): RILEM Publications SARL; 1999. p. 173-83.
32. Barba Pingarrón L, Vaillaseñor Alonso I. La Cal: historia, propiedades y usos [Lime: history, properties and uses]. Ciudad de México (México): Universidad Nacional Autónoma de México, Instituto de Investigaciones Antropológicas; 2013. Spanish.
33. Coloma Álvarez G. La cal: Es un reactivo químico [Lime: It is a chemical reagent]. Santiago (Chile): Canadian Institute of Mining, Metallurgy and Petroleum, Instituto de Ingenieros de Minas de Chile; 2008. Spanish.
34. Figueiredo C. Properties and performance of lime mortars for conservation: the role of binder chemistry and curing regime [dissertation]. Bath (UK): University of Bath; 2018.
35. Margalha G, Silva AS, Veiga MDR, de Brito J. The influence of slaking time on lime putty. In: Lacasse M, Freitas P de, Corvacho H, editors. XII International Conference on Durability of Building Materials and Componentes. Porto (Portugal): FEUP Edições; 2011. doi: 10.13140/RG.2.1.1887.8483
36. Margalha G, Veiga R, Santos Silva A, Brito J. Traditional methods of mortar preparation: The hot lime mix method. Cement Concrete Comp. 2011;33:796-804.
37. Margalha MG, Veiga MR, De Brito J. The Maturation Time Factor in Lime Putty Quality. Available from: http://cathedral.lnec.pt/publicacoes/c11.pdf. Accessed on 3 Apr 2025.
38. Margalha MG, Silva AS, do Rosário Veiga M, de Brito J, Ball RJ, Allen GC. Microstructural Changes of Lime Putty during Aging. J Mater Civil Eng. 2013;25:1524-32.
39. Midtgaard M, Brajer I, Taube M. Hot-mixed lime mortar: historical and analytical evidence of its use in medieval wall painting plaster. J Architect Conserv. 2020;26:235-46.
40. Ávila F, Puertas E, Gallego R. Characterization of the mechanical and physical properties of stabilized rammed earth: A review. Constr Build Mater. 2022;325:126693.
41. Baldovino JA, Izzo RL, Moreira EB, Rose JL. Optimizing the evolution of strength for lime-stabilized rammed soil. J Rock Mech Geotech Eng. 2019;11:882-91.
42. Bell FG. Lime stabilization of clay minerals and soils. Eng Geol. 1996;42:223-37.
43. Deep G. Influence of lime and chicken mesh on compaction behaviour and strength properties of soil. Mater Today Proc. 2020;37:2872-5.
44. Islam S, Hoque NMR, Hoque MA, Mishra PN, Mamun MMH, Dey S. Strength development in fine-grained paddy field soil by lime addition. J Build Eng. 2019;26:100857.

45. Jha AK, Sivapullaiah PV. Lime Stabilization of Soil: A Physico-Chemical and Micro-Mechanistic Perspective. Indian Geotech J. 2020;50:339-47.
46. Arto I, Gallego R, Cifuentes H, Puertas E, Gutiérrez-Carrillo ML. Fracture behavior of rammed earth in historic buildings. Constr Build Mater. 2021;289:123-67.
47. Ávila F, Puertas E, Gallego R. Mechanical characterization of lime-stabilized rammed earth: Lime content and strength development. Constr Build Mater. 2022;350:128871.
48. Canivell J, Martin-del-Rio JJ, Alejandre FJ, 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;191:826-36.
49. Ciancio D, Beckett CTS, Carraro JAH. Optimum lime content identification for lime-stabilised rammed earth. Constr Build Mater. 2014;53:59-65.
50. Da Rocha CG, Consoli NC, Dalla Rosa Johann A. Greening stabilized rammed earth: Devising more sustainable dosages based on strength controlling equations. J Clean Prod. 2014;66:19-26.
51. Fuentes-García R, Valverde-Palacios I, Valverde-Espinosa I. A new procedure to adapt any type of soil for the consolidation and construction of earthen structures: Projected earth system. Mater Constr. 2015;65:e063.
52. AENOR. UNE-EN ISO 17892-4:2019: Geotechnical investigation and testing—Laboratory testing of soil—Part 4: Determination of particle size distribution (ISO 17892-4:2016). Madrid (Spain): Asociación Española de Normalización; 2019.
53. ISO. ISO 14688-2:2018: Geotechnical investigation and testing—Identification and classification of soil—Part 2: Principles for a classification. Geneva (Switzerland): International Organization for Standardization; 2018.
54. AENOR. UNE-EN 459-1:2015: Building lime—Part 1: Definitions, specifications and conformity criteria. Madrid (Spain): Asociación Española de Normalización; 2015.
55. Thompson D, Augarde C, Osorio JP. A review of current construction guidelines to inform the design of rammed earth houses in seismically active zones. J Build Eng. 2022;54:104666.
56. Ávila F, Fagone M, Gallego R, Puertas E, Ranocchiai G. Experimental and numerical evaluation of the compressive and shear behavior of unstabilized rammed earth. Mater Struct. 2023;56:118.
57. Koutous A, Hilali E. Compression stress-strain curve of rammed earth: Measuring and modelling. Results Eng. 2023;18:101012.
58. Walker P, Keable R, Martin J, Maniatidis V. Rammed Earth Design and Construction Guidelines. London (UK): BRE Press; 2005.
59. Raavi SSD, Tripura DD. Predicting and evaluating the engineering properties of unstabilized and cement stabilized fibre reinforced rammed earth blocks. Constr Build Mater. 2020;262:120845.
60. Bui QB, Morel JC. Assessing the anisotropy of rammed earth. Constr Build Mater. 2009;23:3005-11.

61. Kanan MI. Manual de Conservação e Intervenção em Argamassas e Revestimentos à Base de Cal [Manual of Conservation and Intervention in Lime-Based Mortars and Coatings]. Brasília (Brasil): IPHAN; 2008. Spanish.
62. Carazas Aedo W. Test Carazas, manual pedagogico: ensayos de correlacion de las tres fases de la materia tierra [Carazas Test, pedagogical manual: correlation tests of the three phases of earth matter]. Grenoble (France): A+terre; 2017. Spanish.
63. Houben H, Guillaud H. Manuel de construction en terre [Earth Construction Manual]. Grenoble (France): CRAterre; 1985. Spanish.
64. Houben H, Guillaud H. Earth construction technology. Nairobi (Kenia): United Nations Centre For Human Settlements HABITAT; 1992.
65. Heravi G, Abdolvand MM. Assessment of water consumption during production of material and construction phases of residential building projects. Sustain Cities Soc. 2019;51:101785.
66. Seymour LM, Maragh J, Sabatini P, Di Tommaso M, Weaver JC, Masic A. Hot mixing: Mechanistic insights into the durability of ancient Roman concrete. Sci Adv. 2023;9(1):eadd1602.
67. Barbero-Barrera MM, Jové-Sandoval F, González Iglesias S. Assessment of the effect of natural hydraulic lime on the stabilisation of compressed earth blocks. Constr Build Mater. 2020;260:119877.
68. Los AS, Næraa-Nicolajsen M, Bertelsen IMG. Lime Stabilized Rammed Earth—Influence of Curing and Drying Conditions. In: Amziane S, Merta I, Page J, editors. Bio-Based Building Materials (ICBBM 2023). Cham (Switzerland): Springer; 2023. p. 249-58.
69. Rosell Amigó JR. Algunas consideraciones sobre la cal y sus morteros [Some considerations on lime and its mortars]. Available from: https://upcommons.upc.edu/bitstream/handle/2099/11616/Rosell?sequence=1. Accessed on 3 Apr 2025. Spanish.
70. Rosell Amigó JR. Aportaciones al conocimiento del comportamiento deformacional de pastas de cal: tamaño y formas de las partículas y su viscosidad [Contributions to the knowledge of the deformational behavior of lime pastes: particle size and shape and their viscosity] [dissertation]. Barcelona (Spain): Universitat Politècnica de Catalunya, 2013. Spanish.

How to cite this article:
Milleto C, Vegas F, Hueto-Escobar A, Manzano-Férnandez S. Towards the Recovery of Traditional Hot-Mixed Lime Techniques: Influence on the Construction Process and Structural Behaviour in Rammed Earth with Lime. J Sustain Res. 2025;7(2):e250021. https://doi.org/10.20900/jsr20250021