EXPERIMENTAL EVALUATION OF THE OPTIMUM LIME CONTENT AND STRENGTH DEVELOPMENT OF LIME-STABILIZED RAMMED EARTH

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ABSTRACT

The increasing resource consumption, waste generation, and carbon footprint in the construction sector has drawn the attention of builders and researchers to alternative sustainable construction techniques and materials, such as rammed earth (RE). The mechanical behavior of RE is often enhanced through the use of diverse additives; although cement is probably the most common one, lime stabilization provides some important advantages, representing a more efficient and environmentally friendly solution with a long tradition in the improvement of the mechanical and hydraulic behavior of earthen materials. However, there are still several aspects regarding the effect of lime stabilization in RE mechanical properties that have not been thoroughly evaluated. In this regard, the present study analyze two of the main parameters concerning lime-stabilized rammed earth (LSRE), which are essential to ensure the correct use of this technique: the optimum lime content and the curing time. Several RE specimens with different lime contents, from 0 to 18% by weight, were manufactured and subjected to unconfined compression tests in order to obtain and compare their uniaxial compressive strength (UCS) and elastic modulus. An optimum lime content equal to 12% was obtained. Then, more LSRE samples with 12% lime were manufactured and tested at increasing curing times during 100 days to evaluate the development of their strength and stiffness. The results showed a logarithmic growth of both the UCS and the elastic modulus, with the majority of the strength (over 80%) developed during the first 30 days. In addition, non-destructive ultrasonic pulse velocity tests were carried out on the samples, proving to be a useful tool for predicting the mechanical properties of the material without damaging the specimens.
Keywords: lime stabilization, mechanical characterization, optimum lime content, rammed earth, strength development.

1 INTRODUCTION

World's increasing demand for housing and other buildings has led to the consumption of huge amounts of natural resources, waste generation, and pollution. This situation has drawn the attention of builders and researchers for alternative sustainable construction techniques and materials; one such technique that is getting growing interest over the last few decades is rammed earth (RE).

RE has been used in many regions all over the world since ancient times [1–3] as a useful solution to provide decent housing at low price by using locally available materials without requiring highly qualified labor. RE building technique consist of compacting earth layers between temporary formworks to create walls with a thickness commonly between 30 and 60 cm [4–6]. When clay acts as the only binder of the earth mixture, it is referred to as unstabilized rammed earth (URE), but nowadays, it is quite common to stabilize RE with diverse additives in order to improve its mechanical properties and its durability, leading to the so-called stabilized RE.

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Lime is one of the stabilizers that has been traditionally used to enhance RE mechanical and hygric behavior. Lime-stabilized rammed earth (LSRE) could represent a more efficient and environmentally friendly solution than other common stabilizers, such as cement, to improve the mechanical properties of RE constructions [5, 7]; reducing the carbon emissions during the production process and absorbing CO_2 during its lifetime due to the carbonation reaction [7–9].

Although there is a long tradition in using lime as an stabilizer for RE construction and the fact that the benefits of lime to improve the mechanical and hygric behavior of soils are well-known [10–14], there are still many aspect regarding LSRE that have not been yet thoroughly studied. Two of the more relevant aspect that should be evaluated in order to understand the mechanical behavior of LSRE are the optimum lime content and the strength development process. Ciancio et al. [5] considered a curing period of 28 days and indicated an optimum lime content of 4% by weight, but the study was limited to a maximum of 6% lime. A curing period of 28 days has also been used for stabilized RE in some other investigations [15–18], but a thorough analysis regarding the suitability of this value is still missing. Da Rocha et al. [19] also studied the effect of different lime contents (from 3 to 9%), concluding that the unconfined compressive strength increased with increasing lime contents and indicating much longer curing periods, over 90 days.

The present paper includes, therefore, two investigations regarding these two aspects about LSRE. Firstly, several specimens with different lime contents (from 0 to 18%) were manufactured and subjected to uniaxial compression tests in order to establish the optimum lime content that maximizes the mechanical properties of RE. In the second part of the study, specimens with the optimum lime content were manufactured and tested at different curing times to analyze the strength development process. The evolution of the moisture content, carbonation, and ultrasonic pulse velocity (UPV) are also evaluated over the curing time.

2 MATERIALS AND METHODS

2.1 Materials

The natural soil used as the source material for RE in this study was obtained from a quarry in Padul (Granada, Spain). It was passed through a 10-mm sieve to remove the coarser particles, and then classified as clayey well-graded sand, according to the European Soil Classification System (ESCS, ISO 14688-2:2018). Its particle size distribution (10% fine particles, 64.3% sand, and 25.7% gravel) is in agreement with diverse recent studies regarding stabilized RE [17, 18, 20].

The natural soil was stabilized with natural hydraulic lime NHL 3.5 (European standard EN 459-1:2015), with minimum compressive strength of 3.5 MPa at 28 days. The main components of NHL are portlandite, reactive silicates, and aluminates formed during calcination from the reaction of crushed limestone containing clay or other impurities. NHL had 30% free lime ($CA(OH)_2$), a bulk density equal to 0.67 kg/dm^3 and real density 2.51 kg/cm^3.

2.2 Specimen preparation

For the compression tests, 10-cm-side cubic LSRE specimens were manufactured. The material was prepared by uniformly mixing the natural soil with diverse lime contents and a certain amount of water, in order to reach the optimum moisture content (OMC) and so the

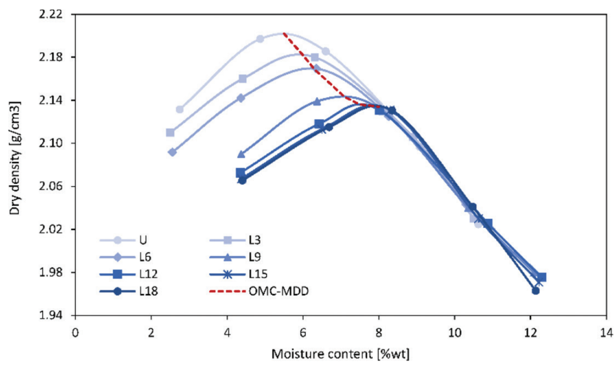

Figure 1: Dry density as a function of the moisture content for the RE mixtures according to Modified Proctor test.

maximum dry density (MDD). The OMC for each RE mixture was determined via Modified Proctor tests [5, 21], according to standard UNE 103501:1994 [22]. The results of this compaction test are shown in Fig. 1 and indicate a linear increase of the OMC with increasing lime contents, while the MDD gradually decreases.

The soil–lime mixture with the OMC was poured in cubic molds and then compacted in five layers of approximately 2 cm. Immediately after manufacture, the samples were carefully removed from the mold and stored on wire racks, where they were cured under constant conditions of ca. 25 °C and 40% relative humidity, allowing specimen water contents to decrease with time [5].

For the first part of the study, specimens with different lime contents were prepared, from 0% lime (i.e., URE) to 18% lime, increasing by 3%. This range widely encompasses the amount of cementitious and calcium stabilizers that have been used in RE literature [1, 5, 15, 23–25]. 18% was established as the maximum lime content because it was considered that greater percentages of lime would lead to an unacceptable increase of the economic and environmental costs. The RE mixtures with 0, 3, 6, 9, 12, 15, and 18% lime are noted as L0, L3, L6, L9, L12, L15, and L15, respectively. These specimens were cured during 28 days before been subjected to uniaxial compression tests.

Once the specimens with increasing lime contents were tested, it was possible to select 12% as the optimum lime content that maximized both the compressive strength and the elastic modulus. Considering this result, several specimens with 12% lime were manufactured in order to evaluate their strength development process over time.

2.3 Experimental evaluation

Uniaxial compression tests were performed in order to obtain the unconfined compressive strength (UCS) and elastic modulus of the LSRE specimens. A distributed load, perpendicular to the direction of the earth layers, was homogeneously applied on the upper face of the sample. A linear variable differential transformer was used to measure the longitudinal displacements for the calculation of the elastic modulus. After the compression tests, the depth of the carbonation front in the specimens was measured by using phenolphthalein solution 1% in ethanol as indicator.

For the 12% lime RE specimens manufactured in the second part of the present study, UCS tests were performed for different curing period from 2 to 100 days. A minimum of three specimens were tested for each curing time, with time intervals between tests smaller during the first weeks (every 2–5 days), as a greater variation of the mechanical properties was expected, and longer for older specimens (every 10 days). During the curing period, the specimens were periodically weighted to control the moisture loss and subjected to ultrasonic pulse velocity tests. UPV nondestructive testing techniques has a long tradition for assessing the mechanical properties and inner cracks of building materials; it is performed using a ultrasonic device, consisting of a transmitting and a receiving transducer, that measures the time of pulse of ultrasonic waves over a known path length [26]. Although UPV method has been widely used for concrete, metal of wooden materials, only a few recent studies have applied it to assess RE mechanical properties [27, 28]. In this study, the UPV is measured in a direction parallel to the earth layers of the LSRE specimens.

3 RESULTS AND DISCUSSION

3.1 Unconfined compression tests

The results from the unconfined compression tests are shown in Fig. 2. The UCS was directly obtained in the test, and the elastic modulus (*E*) is defined as the slope of the tangent line with the elastic part of the stress-strain curved. As the material was observed to present a linear-elastic behavior between 35% and 75% of the maximum stress, the elastic modulus was calculated following eqn (1), where S_{35} and S_{75} are the stresses corresponding to 35% and 75% of the maximum stress, respectively; ε_{35} and ε_{75} and are the longitudinal strains produced by the aforementioned stresses S_{35} and S_{75}, respectively. A similar expression has been used in previous studies [18] to calculate the modulus of elasticity of stabilized RE.

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

Although it is possible to observe a noticeable dispersion, the average coefficients of variation are equal to 11.0% for the UCS and 17.4% for the elastic modulus, which is slightly lower than values presented for stabilized RE in previous studies [18, 29]. The dispersion in the mechanical properties is commonly found in RE materials, due to its intrinsic heterogeneity [30].

According to these results, increasing lime contents generally lead to an increase of the UCS and elastic modulus. However, the UCS reached a maximum of 1.64 MPa for LSRE with 9% lime, meaning an increase of 11% with respect to URE, not obtaining greater strengths with higher lime contents. The elastic modulus, on the other hand, was significantly improved (over 40% compared to URE) for lime contents equal of greater than 12%.

The reason why higher lime contents do not appear to enhance the mechanical properties of RE might be related to the fact that the strength acquired during formation of cementing agents can be counterbalanced, for high lime contents, by an increase of fragility also produce by those cementing agents, leading to a fast generation and propagation of cracks that hasten the failure of the specimen.

Therefore, considering 12% as the optimum lime content for which both the compressive strength and elastic modulus are maximized, several L12 samples are subjected to unconfined compression tests at increasing curing times. The results (Fig. 3) show a logarithmic growth of both the UCS and the elastic modulus, following eqns(2) and (3), with coefficients

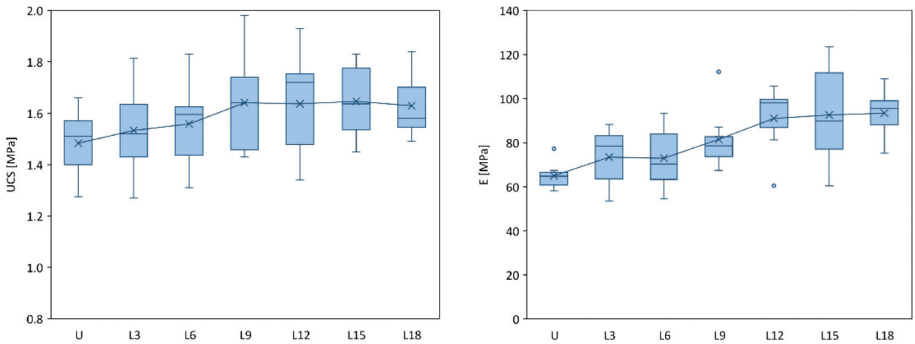

Figure 2: UCS (left) and elastic modulus (right) of RE specimens at 28 days.

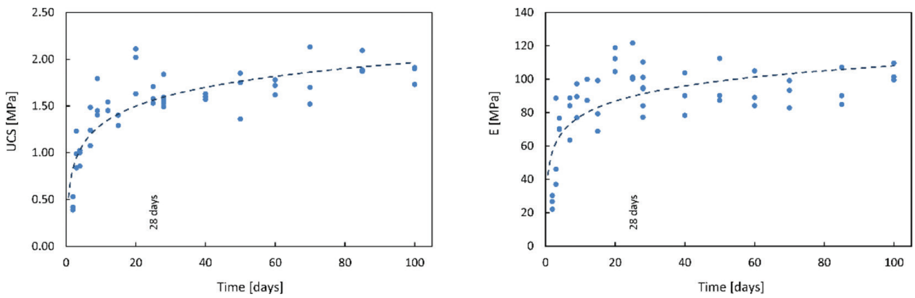

Figure 3: Evolution of UCS (left) and elastic modulus (right) for L12 specimens.

of determination (R^2) of 0.77 and 0.67, respectively. The higher dispersion in the values of the elastic modulus that leads to a lower coefficient of determination has been commonly observed in literature [30].

$$\text{UCS} = 0.290 \cdot \ln(t) + 0.630 \tag{2}$$

$$E = 13.135 \cdot \ln(t) + 47.548 \tag{3}$$

where UCS and E are expressed in MPa, and t is the curing time in days.

The results show that the majority of the UCS (over 80%) and the elastic modulus (ca. 75%) are developed during the first 20–30 days, and then remain practically invariant for longer curing periods.

A linear relationship between the elastic modulus and the UCS was observed for the 12% LSRE specimens according to eqn (4), with $R^2 = 0.75$. Also, the value of the elastic modulus of the tested samples was, with a 95% confidence range, between 46 and 72 times the UCS.

$$E = 55.11 \cdot \text{UCS} \tag{4}$$

3.2 Moisture content and carbonation

Moisture content and carbonation are closely related to the strength development process of RE [5, 31], so it is worthful to analyze their evolution in order to better understand this process. In this regard, the samples were periodically weighted during their curing time in order to estimate the moisture loss. For all the specimens, it was possible to observe that the moisture content drastically diminished during the first week of curing, and then, it gradually stabilizes until day 10–12, remaining almost invariant and equal to ca. 0.80% for longer curing periods.

The carbonation depth was measured, after the unconfined compression tests, as the distance between the external faces of the sample, exposed to CO_2, and the carbonation front. Carbonation at 28 days was observed to be lower for higher lime contents (Fig. 4). Those specimens with higher lime contents have larger amounts of $Ca(OH)_2$ to react with the CO_2 present in the environment, so at the beginning, carbonation may occur faster; however, the quick formation of a carbonated layer hinders the entrance of CO_2 to the inner part of the specimen and so the total time required to reach carbonation in the whole volume of the specimen increases.

Considering the measurements carried out in the present study, the evolution of the carbonation depth (c [mm]) over time (t [days]) for the L12 specimens can be described according to eqn (5), which is a modification of the expression $c = k\sqrt{t}$ proposed by Van Balen and Van Gemert [32] for lime mortars, where k is constant obtained experimentally.

$$c = 4.67 \cdot t^{0.409} \tag{5}$$

In the same way that happens for the other parameters analyzed, carbonation occurs faster during the first days and then slows down. However, in this case, the process is slower, and the carbonation depth continues to increase gradually over hundreds of days until the whole specimen is carbonated. According to eqn (5), the carbonation of the whole 10-cm side cubic specimens would happen at day 331 of curing.

3.3 Ultrasonic pulse velocity

The UPV of L12 specimens was periodically measured during their curing period, showing a logarithmic evolution that indicates a linear relationship between the UCS of the samples and their UPV, also noted in some previous studies [27, 28, 33]. This relationship, with a 95% confidence range, is shown in Fig. 5.

Although the well-known dispersion in the material properties of RE, the relationship between UCS and UPV makes the measurement of the latter a useful method to assess the material properties without damaging the sample, which is particularly interesting to carry out the quality control of new RE structures or to assess the structural state of existing RE building, often with a high heritage value.

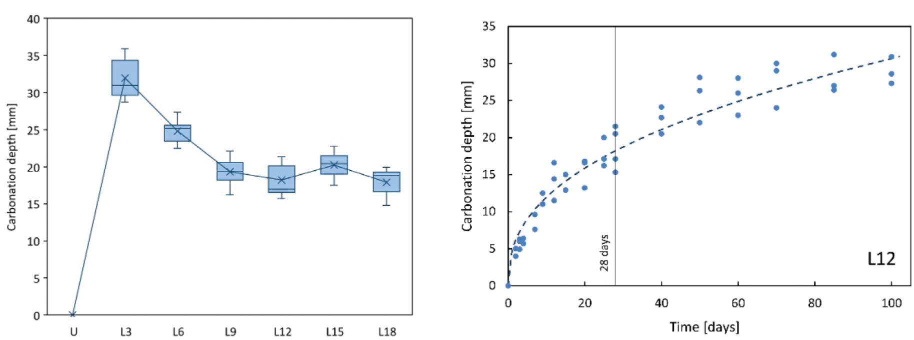

Figure 4: Carbonation depth for different RE mixtures at 28 days (left) and evolution of carbonation during curing time for L12 specimens (right).

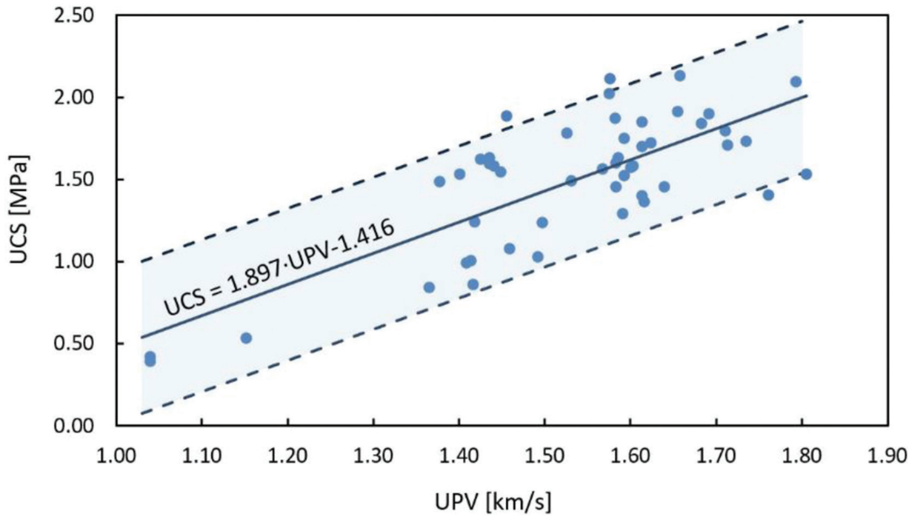

Figure 5: UCS as a function of the ultrasonic pulse velocity.

CONCLUSIONS

RE is increasingly attracting the attention of the construction sector as a sustainable building technique. In order to improve the mechanical behavior of RE, diverse stabilizers, such as lime, are frequently added to the earth mixture. Lime stabilization is a well-known technique to enhance the mechanical and hygric properties of soils and has been used since ancient years in RE stabilization, but there are still several aspects regarding LSRE that should be thoroughly analyzed.

The present paper presents an experimental evaluation of two relevant parameters concerning LSRE that are essential to ensure the correct use of this technique: the optimum lime content and the strength development process. The results from the uniaxial compression tests performed on several RE specimens with different lime contents (from 0 to 18%) indicate that the maximum improvement in the UCS is reached with 9% lime and remains constant for increasing the lime content over that value, while the elastic modulus stabilizes for lime contents equal or greater than 12%.

As stated earlier, 12% is considered as the optimum moisture content that maximizes both UCS and *E*. Considering this, more LSRE samples with 12% lime were manufactured and tested at increasing curing times during 100 days to analyze the strength development process. The results showed a logarithmic growth of both the UCS and the elastic modulus, indicating that the majority of both strength and stiffness is developed during the first 20 to 30 days of curing. The improvement of the mechanical properties during the first month of curing is related to the formation of cementing agents in the presence of water, considered as the main source of strength development [5, 11]. For longer curing periods, the growth of the strength and stiffness drastically slows down, and is probably related to the process of carbonation.

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REFERENCES

[1] Burroughs, S., Recommendations for the selection, stabilization, and compaction of soil for rammed earth wall construction. *J Green Build*, **5(1)**, pp. 101–14, 2010. https://doi.org/10.3992/jgb.5.1.101

[2] Minke, G., *Building with Earth: Design and Technology of a Sustainable Architecture*. Basel, Switzerland: Birkhäuser – Publishers for Architecture, 2006.

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

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

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

[6] El Nabouch, R., Bui, Q.B., Plé, O. & Perrotin, P., Assessing the in-plane seismic performance of rammed earth walls by using horizontal loading tests. *Eng Struct*, **145**, pp. 153–61, 2017. https://doi.org/10.1016/j.engstruct.2017.05.027

[7] Kang, S.-H., Kwon, Y.-H. & Moon, J., Quantitative analysis of CO2 uptake and mechanical properties of air lime-based materials. *Energies*, **12**, p. 2093, 2019. https://doi.org/10.3390/en12152903

[8] Edwards, A.J., Properties of Hydraulic and Non-Hydraulic Limes for Use in Construction [Internet]. Napier University, 2005. https://www.napier.ac.uk/~/media/worktribe/output-252838/edwardspdf.pdf

[9] El-Turki, A., Ball, R.J. & Allen, G.C., Carbonation of natural hydraulic lime (NHL) 3.5. In: Dhir, R.K., Harrison, T.A., Newlands, M.D., eds., *Cement Combinations for Durable Concrete*, Dundee, UK: Thomas Telford Ltd. pp. 300–308, 2005.

[10] Arrieta Baldovino, J. de J., dos Santos Izzo, R.L., Batista Moreira, E. & Lundgren Rose, J., Optimizing the evolution of strength for lime-stabilized rammed soil. *Journal of Rock Mechanics and Geotechnical Engineering*, **11**, pp. 882–91, 2019. https://doi.org/10.1016/j.jrmge.2018.10.008

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

[12] Croft, J.B., The structures of soils stabilized with cementitious agents. *Engineering Geolog*, **2(2)**, pp. 63–80, 1967. https://doi.org/10.1016/0013-7952(67)90025-7

[13] Deep, G., Influence of lime and chicken mesh on compaction behaviour and strength properties of soil. *Materials Today: Proceedings*, 2020. https://doi.org/10.1016/j.matpr.2020.08.663

[14] Islam, S., Hoque, N.M.R., Hoque, M.A., Mishra, P.N., Mamun, M.M.H. & Dey, S., Strength development in fine-grained paddy field soil by lime addition. *Journal of Building Engineering*, **26**, pp. 100857, 2019. https://doi.org/10.1016/j.jobe.2019.100857

[15] Kariyawasam, K.K.G.K.D., & Jayasinghe, C., Cement stabilized rammed earth as a sustainable construction material. *Construction* and *Building Materials*, **105**, pp. 519–527, 2016. https://doi.org/10.1016/j.conbuildmat.2015.12.189

[16] Raavi, S.S.D., & Tripura, D.D., Predicting and evaluating the engineering properties of unstabilized and cement stabilized fibre reinforced rammed earth blocks. *Construction* and *Building Materials*, **262**, p. 120845, 2020. https://doi.org/10.1016/j.conbuildmat.2020.120845

[17] Raj, S., Sharma, A.K. & Anand, K.B., Performance appraisal of coal ash stabilized rammed earth. *Journal of Building Engineering*, **18**, pp. 51–57, 2018. https://doi.org/10.1016/j.jobe.2018.03.001

[18] Toufigh, V. & Kianfar, E., The effects of stabilizers on the thermal and the mechanical properties of rammed earth at various humidities and their environmental impacts. *Construction* and *Building Materials*, **200**, pp. 616–629, 2019. https://doi.org/10.1016/j.conbuildmat.2018.12.050

[19] Da Rocha, C.G., Consoli, N.C. & Dalla Rosa Johann, A., Greening stabilized rammed earth: Devising more sustainable dosages based on strength controlling equations. *Journal of Cleaner Production*, **66**, pp. 19–26, 2014. https://doi.org/10.1016/j.jclepro.2013.11.041

[20] Kosarimovahhed, M. & Toufigh, V., Sustainable usage of waste materials as stabilizer in rammed earth structures. *Journal of Cleaner Production*, **277**, p. 123279, 2020. https://doi.org/10.1016/j.jclepro.2020.123279

[21] El Nabouch, R., Mechanical behavior of rammed earth walls under Pushover tests [Internet]. Université Grenoble Alpes, 2017. https://tel.archives-ouvertes.fr/tel-01707009/document

[22] AENOR, UNE 103501: 1994 Geotecnia. Ensayo de compactación. Proctor modificado. Spain, 1994.

[23] Erdogmus, E. & Garcia, E., Study on the influence of stabilizer type and amount on the compressive strength of compressed stabilized earth block masonry. In: 12th North American Masonry Conference, Denver, Colorado, USA, 2015.

[24] Siddiqua, S. & Barreto, P.N.M., Chemical stabilization of rammed earth using calcium carbide residue and fly ash. *Construction* and *Building Materials*, **169**, pp. 364–371, 2018. https://doi.org/10.1016/j.conbuildmat.2018.02.209

[25] Soudani, L., Modelling and experimental validation of the hygrothermal performances of earth as a building material [Internet]. Université de Lyon, France, 2016. https://hal.inria.fr/tel-01585348/

[26] Kashif Ur Rehman, S., Ibrahim, Z., Memon, S.A. & Jameel, M., Nondestructive test methods for concrete bridges: A review. *Construction* and *Building Materials*, **107**, pp. 58–86, 2016. https://doi.org/10.1016/j.conbuildmat.2015.12.011

[27] 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. *Construction* and *Building Materials*, **191**, pp. 826–36, 2018. https://doi.org/10.1016/j.conbuildmat.2018.09.207

[28] 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. *Construction* and *Building Materials*, **242**, p. 118060 Contents, 2020. https://doi.org/10.1016/j.conbuildmat.2020.118060

[29] Kianfar, E. & Toufigh, V., Reliability analysis of rammed earth structures. *Construction* and *Building Materials*, **127**, pp. 884–95, 2016. https://doi.org/10.1016/j.conbuildmat.2016.10.052

[30] Ávila, F., Puertas, E. & Gallego, R., Characterization of the mechanical and physical properties of unstabilized rammed earth: A review. *Construction* and *Building Materials*, **270**, p. 121435, 2021. https://doi.org/10.1016/j.conbuildmat.2020.121435

[31] Xu, L., Wong, K.K., Fabbri, A., Champiré, F. & Branque, D., Loading-unloading shear behavior of rammed earth upon varying clay content and relative humidity conditions. *Soils and Foundations*, **58(4)**, pp. 1001–1015, 2018. https://doi.org/10.1016/j.sandf.2018.05.005

[32] Van Balen, K. & Van Gemert, D., Modelling lime mortar carbonation. *Materials and Structures*, **27(7)**, pp. 393–398, 1994. https://doi.org/10.1007/BF02473442

[33] Khan, A., Gupta, R. & Garg, M., Determining material characteristics of "Rammed Earth" using non-destructive test methods for structural design. *Structures*, **20**(May), pp. 399–410, 2019. https://doi.org/10.1016/j.istruc.2019.05.003