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Review

# Characterization of the mechanical and physical properties of stabilized rammed earth: A review

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ABSTRACT

Rammed earth is a traditional construction technique that is attracting the interest of the building sector due to its limited cost and very low environmental impact. The use of rammed earth in modern construction, however, often requires an improvement of its properties in order to reach the performance levels fixed by the diverse national and international standards; so rammed earth is frequently improved by the use of different types of additives and stabilizers that, on the other hand, may reduce its environmental and economic benefits. The present study analyzes the alternatives available to enhance rammed earth behavior by reviewing how the existing scientific studies have tried to improve the most relevant mechanical, thermal and acoustic properties.

## 1. Introduction

### *1.1. Background*

Earth has been a very relevant construction material since the beginning of human history, due to its availability at little or no cost, its versatility and its mechanical behavior and insulating properties, both thermal and acoustic [1,2].

Diverse cultures and societies all over the world have developed along time different techniques to use earth for construction: cob, adobe, wattle and daub, etc. One of such techniques with a greater historical and geographical presence is rammed earth (RE) [1,3–5], which consists of compacting a mixture of soil and water in 7.5 to 15 cm-thick layers of [6–9], using temporary formworks, until reaching the desired wall height. These RE walls usually have a thickness between 30 and 60 cm [10–12]. This traditional technique, which only uses soil and water as the source material, with clay acting as the only binder of the mixture, is called unstabilized rammed earth (URE).

The relevance of RE, however, is not a thing of the past. Nowadays, earth construction is attracting the attention of a great number of builders and researchers that are looking for alternative sustainable construction techniques, in the framework of a growing environmental awareness in the construction sector [6,13–15].

However, when rammed earth technique is to be applied in new constructions, its mechanical performance is frequently not good enough to reach the values defined by the building standards. To improve these mechanical properties, and also some other aspects such as the thermal and acoustic behavior, diverse additives can be added to the earth and water mixture, leading to the so-called stabilized rammed earth (SRE). There exist diverse additives or stabilizers that improve the behavior of RE by physical and chemical interactions with the soil particles and the water present in the mixture; some of these additives have been used since antiquity (e.g. lime or natural fiber [3,16,17]) and some others have been introduced in the last decades or years (e.g. cement, coal combustion residuals, artificial fibers or advanced materials) [2,5,18].

The use of stabilizers in RE is becoming more and more frequent, improving its properties and allowing to use this technique in a wider range of constructions. However, if additivation is used systematically and without taking enough care about which are the requirements that URE cannot fulfill, there is the risk that RE constructions lose some of the most important properties (i.e. low cost and low environmental impact) that make this technique interesting and useful nowadays [19–21].

### *1.2. Focus and research questions*

Considering the above, this document analyzes the state of the art of SRE, aiming to present the different options for RE stabilization, from the point of view of the property that needs to be improved, in order to make it easier for researchers and builders to choose the best alternative and to understand the consequences (mechanical, environmental and economical) derived from the stabilization.

To reach this goal, this study is divided in five parts, including the mains aspects to be considered when choosing a construction technique

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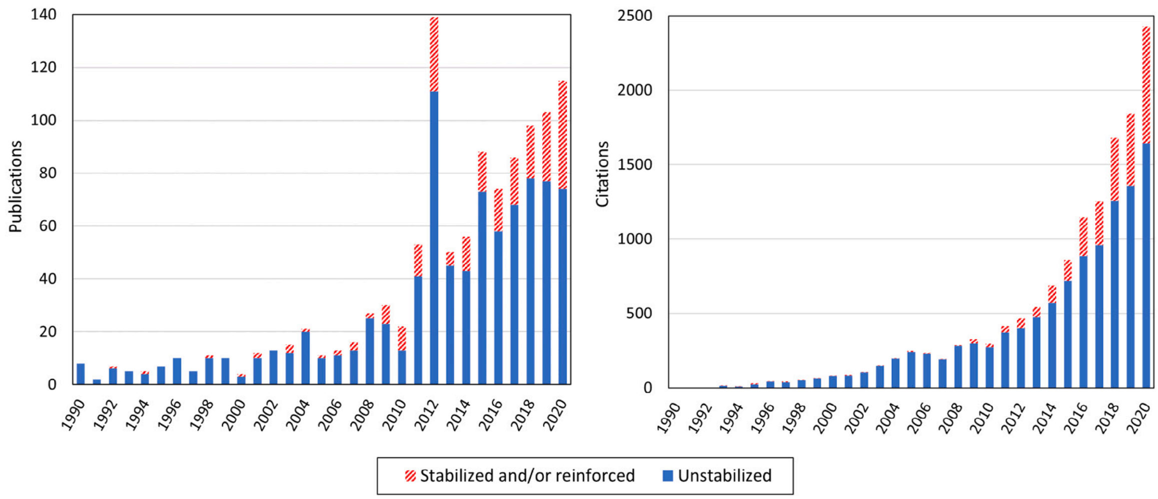


**Fig. 1.** Publications and citations in Web of Science regarding rammed earth that include or not the words "stabilized" and/or "reinforced", between the years 1990 and 2020.

or material. The first one presents the main stabilizers that have been commonly used in rammed earth construction, their characteristics and the characteristics of the soil to be used for stabilization. The second and third parts regard the mechanical behavior and insulating properties of SRE, focusing on how each kind of stabilizer is used to enhance each parameter. Then the durability is analyzed, as one of the greatest concerns about rammed earth structures. Finally, the last sections evaluates the environmental and economic impact of this building technique, focusing on how the use of stabilizers could affect some of the main benefits of traditional RE construction.

## 2. Materials

### 2.1. Stabilizers, additives and reinforcements

As mentioned above, natural soil can be directly used to build RE structures, but when higher strength or durability are required it is common to add different kinds of additives to the mixture. The growing interest in the use of additives and reinforcements to improve the mechanical and physical behavior of RE can be noted observing the increasing number of scientific publications regarding RE construction, and their citations, that refer to stabilization (Fig. 1).

Portland cement is, by far, the most frequently used stabilizer nowadays [18,22], substantially improving the compressive strength and durability of RE elements [19,23,24]. Natural soil to be used for cement stabilization must have a reduced clay content, so the shrinkage of the resulting RE material is also lower than the one observed in URE. These mechanical improvements have made cement stabilization a generally accepted routine practice in RE construction in countries such as Australia, New Zealand or the United States, but its use should be limited due to the severe increase in environmental costs [19–21].

Another RE stabilizer with a long tradition is lime. There is a broad consensus that lime stabilization improves the mechanical and hydraulic behavior of soils [25–29]. When lime is added to a soil, the concentration of $Ca^{2+}$ and $OH^{-}$ increases due to the hydration reaction of lime. This generates the flocculation of particles, affecting soil plasticity, and an increase in pH, causing the dissolution of silica and alumina from soil minerals, which react with calcium forming calcium silicate (or aluminate) hydrates that cement soil particles and increase the mechanical performance of the material [26,30].

The benefits of lime stabilization of RE have been known since ancient times, being possible to find several examples of historic buildings made of LSRE [31–34]. However, and despite its historical use, lime has been superseded by cement as the main additive to improve the mechanical properties of RE during the last decades, and as a consequence there are few scientific studies dealing with lime-stabilized rammed earth (LSRE).

Usually combined with cement or lime, fly ash (FA) is sometimes added to the RE mixture to increase the amount of amorphous material available and to enhance the cementitious reactions between soil and the main stabilizer [35]. Since FA is a residue generated by coal combustion, its use helps reducing the environmental impacts of cement-stabilized rammed earth (CSRE) [19,23,36]. With the same aim of obtaining a more sustainable stabilized material, several studies have proposed over the last years the addition of other waste materials to RE, such as bottom ash (BA) [37], recycled concrete aggregates [38], calcium carbide residue (CCR) [39,40], ground granulated blast furnace slag [41] or brick waste [36].

In addition to the aforementioned binders used to improve the properties of RE by chemical stabilization, there is another type of additives that enhance the mechanical behavior of RE by means of their shape: fibers. To highlight the different approaches between cement or lime stabilization and fiber stabilization, the latter is sometimes referred to as "fiber-reinforced" rammed earth [16], instead of "fiber-stabilized". It is important to distinguish, nevertheless, whether fibers are used in the form of single short pieces included in the earth mixture or if they are use in the form of fabrics acting as external or internal structural reinforcements [42–44]. Considering the enormous variety of plant aggregates and natural fibers that have been commonly added to earthen construction materials since antiquity [1,45], it is difficult to establish a comprehensive list or classification; however, Laborel-Préneron et al. [17] proposed to group them in eight categories: cereal straws, wood aggregates, bast fibers, palm tree fibers, waste and residues, leaf fibers, aquatic plant fibers and chips, and sheep wool. Over the last years, some authors have also proposed the stabilization of RE with non-natural fibers, such as fiberglass [22], polypropylene fiber [46] or waste tire fibers [47], although they have very small use yet and the knowledge regarding their mechanical effects on RE is still limited.

### 2.2. Soil

Stabilization techniques can be used to improve the mechanical properties of a soil that initially would not be appropriate for RE construction. However, if the goal is to obtain an excellent mechanical performance, the soil should meet some requirements. Burroughs [4] recommended, for cement or lime stabilization, using a soil with linear shrinkage lower than 11 % according to Australian Standard [48], sand content lower than 64 % and fine particles preferably between 21 % and 35 %.

These values of the particle size distribution are in agreement with the ones proposed by Maniatidis and Walker [18] for URE (clay and silt combined between 20 % and 35 % and sand between 50 % and 75 %) and with the envelopes recommended by Houben et al. [49], which are frequently used in URE literature [50]. Maniatidis and Walker [18] also noted that, in order to optimize the benefits of stabilization, soil should mainly consist of sand and fine gravel, with only enough clay to provide cohesive strength and a percentage of silt to act as void filler. As the additive is acting as a binder in SRE, the binding effect of clay is not as important as for URE, and also the presence of clay generally impedes effectiveness of cement stabilization. According to The Australian Earth Building Handbook [51], when using lime as stabilizer the ideal soil should have a plasticity index from 20 % to 30 % and liquid limit between 25 and 50, so lime would be particularly appropriate for stabilization of expansive soils [52].

Also, for SRE, soil should generally be free of humus and plant matter to prevent later deterioration; although under certain conditions, plant matter such as dry straw could be added [53].

### 2.3. Moisture content and density

The moisture content during manufacturing is known to be an important factor for the strength development of RE [15]. Generally, a value close to the optimum moisture content (OMC), which allows the maximum dry density of the soil for a certain compaction energy, is chosen [50]. Walker et al. [15] recommend adding the OMC ± 1 % to 2 %, while the New Zealand Standard NZS4298 [54] indicates that the moisture content before compaction should be within 3 % of the OMC and never more than 4 % dry or 6 % wet of optimum.

This OMC is determined in most of the studies via Standard or Modified Proctor tests. The Modified Proctor test uses higher compaction energy so the OMC obtained is slightly lower, which, according to some authors [55,56] would be closer to the compaction effort applied in the construction of a real wall by mechanics means. However, some standards, as the aforementioned NZS4298, specify that the OMC should be obtained via Standard Proctor or equivalent. An alternative to easily assess the correct water content for the mixture is performing the so-called “drop test” [18,51,54,57], consisting on compacting by hand a ball of moist soil that is then dropped onto a hard flat surface from a height of ca. 1.5 m. When the soil is too dry the ball breaks into several pieces, if it is close to the OMC the ball breaks into only a few pieces, and if the soil is too wet then the ball remains in one piece.

Despite the existing agreement in using moisture contents similar to the OMC, when additives are included it is not always easy to evaluate the OMC of the mixture. For example, for lime or cement-SRE, oven drying cannot be used to assess the water content due to the loss of non-evaporable water via chemical reactions (cation exchange, flocculation and pozzolanic reactions) [55]. Some authors, therefore, calculate the OMC of the soil (unstabilized) and directly use it for all the mixtures [35,36,58], or calculate the OMC of the soil and then use that value +1 % for the stabilized samples [16].

These procedural simplifications can be considered reasonable if one observes the values obtained by the authors that did vary the moisture content depending on the amount of stabilizer added: Ciancio et al. [55] obtained an OMC between 7.6 % and 9.6 % for lime contents from 0 % to 6 %, Toufigh and Kianfar [22] used a moisture content between 12 % and 13 % for cement contents from 2.5 % to 10 % and also for other additives (guar gum, pozzolanics or fiberglass), and Tripura and Singh [24] indicated water contents around 19 % for 4 % to 10 % CSRE. It can be observed that the variation in the OMC is very small, as indicated by Hallal et al. [58], and always within the range of acceptance suggested by Walker et al. [15] and NZS4298 [54]. In fact, most studies regarding SRE use moisture values between 8 % and 14 % [3,22,36,39,41,43,55,59–61], which is an interval very similar to the one observed for URE studies [50].

**Table 1**
Moisture content (MC), unconfined compressive strength and elastic modulus of SRE samples (in parenthesis improvement of UCS and $E$ with respect to URE, when available). Mixture with highest UCS for each study. Additives abbreviations: Cem - cement; FA - fly ash; BA - bottom ash; CCR - calcium carbide residue; WTTF - waste tire textile fibers.

| Ref. | Sample [cm] | Additives (%wt) | MC [%wt] | UCS [MPa] | $E$ [MPa] |
|---|---|---|---|---|---|
| [55] | ⌀10, $h = 20$ | Lime (5) | 10 | 1.2 (71 %) | 175 (84 %) |
| [35] | ⌀5, $h = 10$ | Lime(3)+FA(28) | 14 | 1.3 | – |
| [37] | ⌀3.8, $h = 7$ | Cem(6)+FA(12)+BA(18) | 10 | 2.5 | 118 |
| [59] | 100 × 160 × 65 | Cem (10) | 13 | 3.1 | – |
| [16] | ⌀10, $h = 20$ | Cem (6) | 12 | 3.2 (60 %) | 801 (136 %) |
| [36] | 15 × 15 × 15 | Cem (20) | 13 | 3.3 (240 %) | – |
| [58] | ⌀10, $h = 20$ | Lime(4)+Cem(4) | 18 | 4.8 (272 %) | 355 (788 %) |
| [46] | ⌀10.2, $h = 11.6$ | Cem(6) | 12 | 4.9 | – |
| [40] | ⌀4, $h = 8$ | FA(5)+CCR(7) | 14 | 5.2 | – |
| [22] | ⌀7.5, $h = 15$ | Cem (10) | 13 | 5.2 (133 %) | 740 (417 %) |
| [39] | ⌀10, $h = 20$ | Cem(5)+FA(5) | 8 | 5.3 (300 %) | – |
| [60] | ⌀7.5, $h = 15$ | Cem (10) | 13 | 5.4 (182 %) | – |
| [47] | ⌀7.1, $h = 14.2$ | Cem(7)+WTTF(1) | – | 6.2 (65 %) | 416 (22 %) |
| [14] | 10 × 10 × 10 | Cem (10) | 16 | 6.5 (69 %) | – |
| [24] | 10 × 10 × 10 | Cem (10) | 19 | 7.4 (575 %) | – |
| [61] | ⌀10.4, $h = 20$ | Cem (8) | 9 | 9.4 | 1166 |
| [38] | ⌀10, $h = 20$ | Cem (7) | 7 | 10.0 | – |
| [41] | ⌀10.4, $h = 20$ | Cem (8) | 10 | 11.1 | 7500 |

## 3. Mechanical properties

### 3.1. Unconfined compressive strength

The unconfined compressive strength (UCS) has always been the main parameter to characterize the mechanical behavior of RE (stabilized and unstabilized), as it happens with most brittle materials. Additives used with the aim of increasing the tensile or flexural strength of RE have also been studied but their presence in literature is much more limited.

The compressive strength is obtained via uniaxial compression tests perpendicularly to the direction of the earth layers, mainly on small cylindrical samples with diameter equal to twice the height, although cubic specimens of diverse sizes have also been used [50]. The manufacturing and testing techniques also vary, due to the lack of an international standard that prescribed the test procedure for the determination of the UCS of RE samples. It would be essential to develop a standardized test procedure for this material in order to actually make the results obtained by the diverse studies fully comparable.

Table 1 shows the UCS and elastic modulus obtained in several recent studies regarding SRE. The table shows that the most commonly used additive to maximize the compressive strength of the soil mixture is cement, sometimes combined with other additives (particularly fly ash). With high cement contents, around 10 %, it is possible to obtain very high compressive strength, over 5 MPa, meaning an improvement between 1.5 and 5 times the UCS of URE, even reaching a strength 10 MPa in some cases. Lime is also used to enhance the compressive strength of RE, but the improvement is smaller, always under 5 MPa, with common lime contents between 3 % and 5 %.

As mentioned before, the water content at manufacturing is quite homogeneous, generally between 10 % and 13 %, with only a few exceptions [24,58] using moisture contents near 20 %.

It should be noted that available data from literature does not allow the present study to evaluate or compare the suction conditions of the samples. Nevertheless, it can be mentioned that suction is a key parameter affecting the structural integrity of RE under moisture movement and is the source of strength in URE materials [62,63]. The influence of suction is more relevant in LSRE, while its effect is almost negligible on cement stabilization due to the disproportionate increase in strength and stiffness for the latter method.

Because of the relevance, effectiveness and widespread use of cement to improve the compressive strength of RE, it is worthwhile

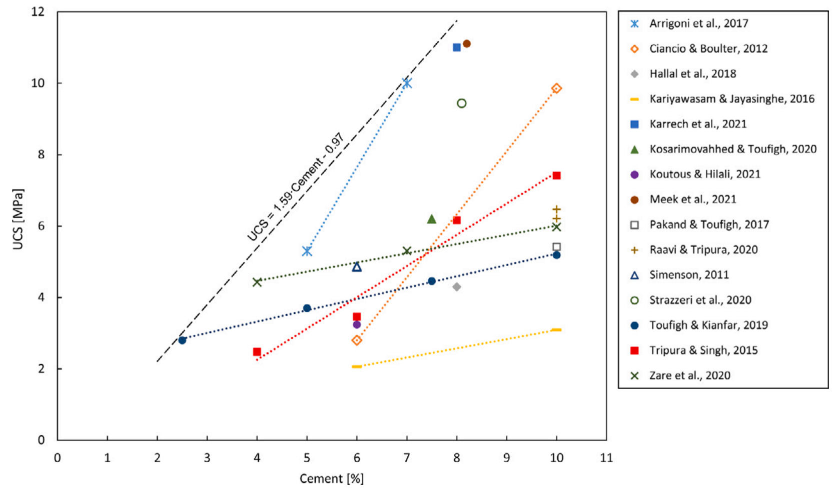


**Fig. 2.** Unconfined compressive strength of CSRE as a function of cement content. Values obtained by Arrigoni et al. [39], Ciancio & Boulter [20], Hallal et al. [58], Kariyawasam & Jayasinghe [59], Karrech et al. [67], Kosarimovahhed & Toufigh [23], Koutous & Hilali [16], Meek et al. [41], Pakand & Toufigh [60], Raavi & Tripura [14], Simenson [46], Strazzeri et al. [61], Toufigh & Kianfar [22], Tripura & Singh [24] and Zare et al. [47].

to specifically evaluate the relationship between cement content and UCS. Fig. 2 represents the results of several studies regarding cement stabilization of RE. Although there is a significant dispersion, some conclusions can be drawn: there seems to be an upper limit for the compressive strength depending the percentage of cement (UCS [MPa] < 1.59 Cement [%] – 0.97) and a lower limit of ca. 2 MPa (so always above the minimum requirements indicated in most existing standards, which are between 1.3 MPa and 2 MPa [54,64–66]); and for a certain soil and testing conditions there is a linear relationship between the cement content and the UCS of the SRE, according to all the studies in which more than two cement contents were tested.

### 3.2. Young modulus and Poisson's ratio

When performing uniaxial compression tests to obtain the UCS of SRE, it is common to calculate also the elastic modulus ($E$) of the material as the slope of the tangent line with the elastic part of the stress–strain curve [37,47,55,58,61]. Toufigh and Kianfar [22], who performed UCS test for several SRE mixtures, proposed calculating the elastic modulus according Eq. (1), following the procedure indicated for concrete in standard ASTM C469 [68], also used in [23].

$$E = (\sigma_2 - \sigma_1)/(\varepsilon - 5 \cdot 10^{-5}) \tag{1}$$

where $\sigma_2$ is the stress corresponding to 40 % of ultimate load, $\sigma_1$ is stress corresponding to a longitudinal strain of $5 \cdot 10^{-5}$ and $\varepsilon$ is longitudinal strain produced by stress $\sigma_2$. However, there is not a consensus in the formulation of the elastic modulus; other authors [16] propose using the secant modulus (ratio between maximum stress and corresponding peak strain) as the best parameter to describe the elastoplastic mechanical behavior of earthen materials, indicating a value of the secant modulus equal to approximately 0.62 times the initial tangent modulus for URE, CSRE and LSRE. Xu et al. [69] calculated the Young's modulus of URE performing loading–unloading triaxial test and applying the following equation:

$$E = \Delta\sigma_{xx}^{cycle} / \Delta\varepsilon_{xx}^{cycle} \tag{2}$$

where $\Delta\sigma_{xx}^{cycle}$ and $\Delta\varepsilon_{xx}^{cycle}$ are the differences in axial stress and axial strain, respectively, between the maximal and minimal load cycles.

As it can be observed in Table 1 and Fig. 3, there is a significant dispersion in the values of the elastic modulus obtained by diverse studies. This dispersion is partially due to the use of different additives, but might be also caused by the variability in the manufacturing and testing techniques and also intrinsic to the heterogeneity of the material, as it was also noted for URE [50]. In Fig. 3 it is also possible to observe that most studies indicate a direct relation between UCS and the elastic modulus, so $E$ is expected to increase with increasing UCS, although the dispersion in the results does not allow to define a clear correlation.

As it happens with the compressive strength, cement is the most common stabilizer added to RE to improve its elastic modulus. Studies regarding CSRE [16,22,47,58,61] indicate elastic modulus within the range from 250 MPa to 750 MPa using cement contents between 2 % and 10 %. The same studies indicate that those values lead to an improvement of 150 % to 500 % with respect to URE specimens. Smaller improvements of the elastic modulus (40 % to 140 %) are obtained when using lime as stabilizer [16,55].

Regarding the Poisson's ratio ($\nu$), there are only a few studies calculating its value. Raj et al. [37] and Meek et al. [41] obtained values between 0.16 and 0.20 for RE stabilized with diverse additives including cement, fly and bottom ash, ground-granulated blast-furnace slag and kaolin clay, while Strazzeri et al. [61] obtained a $\nu$ value of 0.33 for CSRE with and without expanded polystyrene.

### 3.3. Tensile and flexural strength

Rammed earth is known to be very weak in tension, so RE elements should not be designed for pure tension [18]. However, the tensile strength ($f_t$) is a very relevant parameter involved in RE failure, especially under extreme loading conditions, such as earthquakes [70,71]. These are the main reasons why several authors have tried to improve RE tensile strength by stabilization, as shown in Table 2. It can be seen that the value of $f_t$ in these studies reaches values in the range from 0.25 to 1.16 MPa, and in most of them above 0.4 MPa, which is an improvement over URE frequently above 150 percent.

The most commonly used additive to improve RE tensile strength are fibers [17,18], both natural (straw, palm, coir, jute, barley,...) [14,16,58] or synthetic (fiberglass, plastic fibers) [22,47]. According to The Australian Earth Building Handbook [51], the ideal soil for fiber stabilization should have liquid limit between 30 % and 50 % and plasticity index between 15 and 35.

Fiber stabilization, however, frequently implies a reduction of the compressive strength with increasing fiber contents [47,53]. This fact can be counterbalanced with the combined use of fibers and cement as evaluated by Zare et al. [47] who tried different combinations with diverse contents of cement and waste tire fibers. Actually, the highest $f_t$ values, according to literature, are obtained adding both fibers and cement to the soil mixture [14,47,58].

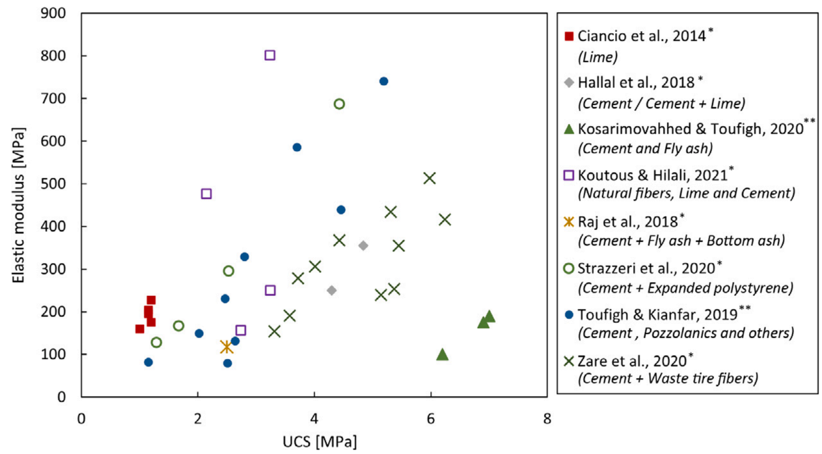


**Fig. 3.** Elastic modulus of SRE as a function of unconfined compressive strength. Values obtained by Ciancio et al. [55], Hallal et al. [58], Kosarimovahhed & Toufigh [23], Koutous & Hilali [16], Raj et al. [37], Strazzeri et al. [61], Toufigh & Kianfar [22] and Zare et al. [47].
*Elastic modulus as the slope of $\sigma-\varepsilon$ curve in its elastic area (tangent modulus).
**Elastic modulus calculated according to Eq. (1).

**Table 2**
Tensile strength ($f_t$) and unconfined compressive strength of SRE samples (in parenthesis improvement of UCS and $f_t$ with respect to URE, when available). Additives abbreviations: Pozz - pozzolanics; Cem - cement; HF - hemp fiber; WTTF - waste tire textile fibers. *Percent by volume.

| Ref. | Sample [cm] | Additives (%wt) | $f_t$ [MPa] | UCS [MPa] | Ratio $f_t$/UCS |
|---|---|---|---|---|---|
| [22] | ⌀7.5, $h=15$ | Pozz(10)+Microsilica(1.5) | 0.25 (4 %) | 2.5 (11 %) | 0.10 |
| [58] | ⌀10, $h=20$ | Cem (8) | 0.33 (106 %) | 4.3 (231 %) | 0.08 |
| [14] | 10 × 10 × 10 | Coir fiber (3) | 0.39 (179 %) | 4.1 (7 %) | 0.10 |
| [16] | ⌀10, $h=20$ | Lime (4) | 0.40 (0 %) | 2.2 (6 %) | 0.18 |
| [16] | ⌀10, $h=20$ | Cem (6) | 0.45 (13 %) | 3.2 (60 %) | 0.14 |
| [16] | ⌀10, $h=20$ | Palm fiber (0.75) | 0.45 (13 %) | 3.3 (60 %) | 0.14 |
| [3] | 44 × 10 × 10 | Lime (25*) | 0.49 | – | – |
| [16] | ⌀10, $h=20$ | Barley fiber (0.75) | 0.50 (25 %) | 2.7 (35 %) | 0.19 |
| [22] | ⌀7.5, $h=15$ | Fiberglass (1.5) | 0.53 (121 %) | 2.5 (13 %) | 0.21 |
| [47] | 40 × 10 × 10 | WTTF (4) | 0.68 (155 %) | 3.3 (−12 %) | 0.21 |
| [22] | ⌀7.5, $h=15$ | Cem (10) | 0.77 (221 %) | 5.2 (133 %) | 0.15 |
| [47] | 40 × 10 × 10 | Cem(7)+WTTF(4) | 0.89 (231 %) | 5.2 (36 %) | 0.17 |
| [58] | ⌀10, $h=20$ | Cem(4)+Lime(2)+HF(1.25) | 0.96 (500 %) | – | – |
| [14] | 10 × 10 × 10 | Cem(10) | 0.99 (607 %) | 6.5 (69 %) | 0.15 |
| [14] | 10 × 10 × 10 | Cem(10)+Coir fiber(3) | 1.16 (729 %) | 6.2 (63 %) | 0.19 |

The improvement of RE tensile strength also leads to an increase in the $f_t$/UCS ratio. If this ratio was approximately equal to 0.10 for URE [50], it raises to between 0.10 and 0.21 in the case of SRE.

There are few studies regarding the flexural strength of RE materials, both unstabilized and stabilized. Jayasinghe and Mallawaarachchi [72] performed four-points bending tests in URE walls obtaining a value of 0.46 MPa when the load was applied parallel to the layers and 0.92 MPa if perpendicular. Ciancio and Augarde [73] performed the same tests obtained values of flexural strength similar to the latter, between 0.80 and 1.00 MPa.

With the aim of improving the flexural strength of RE, authors have proposed using fiber reinforcements. Tripura et al. [74] carried out four-points bending tests (parallel and perpendicular to the earth layers) on RE samples combining cement stabilization, cocoa fiber reinforcement (short fibers mixed in the matrix) and bamboo external reinforcements. All combinations of additives resulted in an increase of the flexural strength if compared with URE; the maximum values were reached with combining all three additives, reaching 1.29 MPa for parallel loading (+139 % with respect to URE) and 2.11 MPa for perpendicular loading (+167 %). Also Vernat-Maso et al. [42] performed three-points bending tests to analyze the effect of textile reinforcement in the flexural behavior of rammed earth, concluding that, when the failure mode was not associated with the possible least earth-grid adherence, the reinforced specimens showed a greater load-bearing capacity than that of the unreinforced ones, with an increase in the maximum bending moment of ca. 94 %.

These results indicate that fiber reinforcements (both internal short fibers or structural fabrics) may be very useful to enhance the flexural behavior of RE elements, although further studies would be necessary to draw general conclusions. Also, regarding fabric reinforcements, it essential to ensure the proper adhesion between the reinforcement and the soil matrix in order to obtain the desired improvements in the mechanical behavior of the compound [43].

### 3.4. Shear strength, cohesion and fracture energy

Rammed earth presents very low shear strength [50], so for RE walls it is frequently considered close or equal to zero in absence of further experimental data [51,75]. Although there are currently no studies regarding the enhancement of RE shear strength through additivation, some few studies have evaluated the shear behavior of CSRE.

Lepakshi and Venkatarama [76] carried out triaxial compression tests on several RE cylindrical specimens with cement contents from 4 % to 15 %. The results indicate that increasing cement contents lead to an increase in the shear strength (from 0.59 MPa with 4 % cement to 2.18 MPa with 15 % cement). This last value is much higher than common shear strengths indicated by several authors for URE (0.15–0.85 MPa) [70,77–79].

Pavan et al. [80] performed diagonal compression tests on 10 % CSRE panels according to ASTM-E519 [81] using two different techniques to improve the bond between layers: making blunt conical shaped dents and applying a coat of fresh cement slurry. The shear strength obtained in both cases was equal to 1.24 MPa.

These two studies also evaluated the cohesion and friction angle of CSRE, obtaining the results shown in Table 3. Particularly interesting are the results of Lepakshi and Venkatarama [76], indicating that cohesion linearly grows with increasing cement contents while the angle of internal friction remains almost invariant and equal to ca. 50° for cement contents over 7 %. Also Kosarimovahhed and Toufigh [23] evaluated the cohesion of cement and lime SRE, obtaining a maximum of 1 150 kPa with a combination of 2.5 % cement and 5 % lime.

According to the values of these few studies, shown in Table 3, cement seems to significantly increase the cohesion of RE, which is in the range from 30 kPa to 260 kPa for URE [50]. The increments in the values of the friction angle, on the other hand, are almost negligible.

There are still only a few studies evaluating the fracture energy ($G_f$) of RE, but all of them indicate that the fracture energy of RE could

**Table 3**
Shear strength ($f_s$), cohesion ($c$) and friction angle ($\varphi$) of SRE.

| Ref. | Cement [%wt] | Lime [%wt] | $f_s$ [MPa] | $c$ [kPa] | $\varphi$ [°] |
|---|---|---|---|---|---|
| [76] | 4.0 | – | 0.59 | 480 | 27 |
| | 7.0 | – | 1.16 | 640 | 55 |
| | 10.0 | – | 1.67 | 940 | 52 |
| | 15.0 | – | 2.18 | 1320 | 46 |
| [80] | 10.0[a] | – | 1.24 | 794 | 26 |
| | 10.0[b] | – | 1.24 | 762 | 49 |
| [23] | 7.5 | – | – | 205 | – |
| | 5.0 | 2.5 | – | 490 | – |
| | – | 7.5 | – | 805 | – |
| | 2.5 | 5.0 | – | 1150 | – |

[a]Blunt conical shaped dents between layers.
[b]Coat of fresh cement slurry between layers.

be improved by chemical additivation (lime or cement). Three-points bending tests and splitting tensile tests were performed to determine this parameter. Arto et al. [3] identified a clear correlation between the fracture energy and the soil-lime ratio, reaching values over 30 N/m with 25 % vol lime. Corbin and Augarde [82] obtained an approximately linear relationship between $G_f$ and cement content, from only 1.5 N/m for URE to 36 N/m for 10 % CSRE. Higher values were reported by Sajad and Toufigh [63]: $G_f = 20$ N/m for URE and $G_f = 63$ N/m for 10 % CSRE.

According to these investigations, other additives, such as pozzolan, microsilica, guar gum, fiberglass or PCM do not significantly affect the fracture energy [63]; while the addition of wool decreases the $G_f$ values over a 50 % [82].

## 4. Insulating properties

### 4.1. Thermal insulation

URE provides an acceptable thermal insulation, with a thermal conductivity ($\lambda$) between 1.0 and 1.4 $\mathrm{W m^{-1} K^{-1}}$ [50], similar to traditional ceramic bricks [1,83] and better than other common construction materials such as concrete [83]. Considering this, most studies regarding RE stabilization have focused their efforts on improving the mechanical properties and not so much the thermal behavior.

However, it is possible to enhance the thermal performance of RE walls by incorporating thermal energy storage materials, that store energy by sensible or latent heat, such as expanded polystyrene (EPS) or phase change materials (PCM) [60]. This additives can significantly reduce the thermal conductivity of RE, obtaining $\lambda$ values lower than 0.4 $\mathrm{W m^{-1} K^{-1}}$, as shown in Fig. 4 (left).

Karrech et al. [67] reached a 62 % reduction of the thermal conductivity of CSRE with a 20 %vol of polystyrene composite (expanded polystyrene beads coated with a bituminous binding agent); and Pakand and Toufigh [60] reduced $\lambda$ by 24 % using 20 %vol EPS. If PCM are used (about 10 %), the reduction of the thermal conductivity is between 15 and 20 % [60,84].

The problem with this kind of additives is that they significantly worsen the mechanical performance of the RE structure, causing a decrease in the UCS (Fig. 4 (right)). However, when high compressive strengths are important, it should be noted that Pakand and Toufigh [60] indicated that cement stabilization also provides a certain improvement in the thermal behavior, while increasing the mechanical properties.

The effect of moisture content on the thermal behavior of RE should also be taken into account. It has been observed that the thermal conductivity of CSRE linearly increases with the saturation ratio of the material, due to the formation of menisci acting as thermal bridges between particles in partially saturated soils [85,86].

### 4.2. Acoustic performance

As with the thermal behavior, URE shows a very good acoustic performance, and therefore it has not been a priority of researchers to study the improvement of this characteristic via additivation. URE has a sound reduction index ($R$) of about 57 dB for 30 cm to 50 cm-thick walls [15,87–89], and its porosity provides an excellent reverberation behavior, generating far fewer harsh echoes than other common wall materials [87,90,91].

No studies in literature have been found specifically regarding the improvement of these acoustic properties, but deeper investigation in this field would be necessary. In the absence of further research, it would be possible to enhance the acoustic insulation by covering the RE walls with insulating panels, as it is done for any other type of wall.

## 5. Durability

RE construction are quite sensitive to rain and wind erosion and to the effect of aggressive environments, so they frequently need some kind of protection against weathering [19,92–94]. This protection can be obtained with external barriers (waterproofing agents or sloping roofs) or through additivation.

Some studies indicate that the use of cement significantly improves the durability of RE against water erosion. Arrigoni et al. [19] measured the accelerated erosion due to sprayed water and mass loss due to wire brushing on URE and SRE mixtures with 5 % cement + 5 % FA and 6 % CCR + 25 % FA, observing that both SRE mixtures (but not URE) passed the tests and achieved sufficient strengths for construction according to The Australian Earth Building Handbook [51]. Also Narloch and Woyciechowski [95] performed water erosion resistance tests on URE and 6 % and 9 % CSRE according to New Zealand Standard NZS 4298 [54], obtaining that none of the CSRE samples showed any surface damage while all the URE specimens had deep cavities despite their shorter exposure time in water, concluding that in a humid continental climate the use of URE is unsuitable due to lack of durability.

However, some studies evaluating the long-term durability (over 20 years) of RE against water, suggest that external protection is needed also for CSRE [96] or even that the stabilization by cement or lime might be inadequate [97].

Erosion is the major cause of concern for earthen structures, but aggressive environments may also decrease the durability of RE. Although additional durability issues (e.g. alkali-aggregate reactions and sulfate induced swelling) could be expected when cement-like additives are used [19], Ghasemalizadeh and Toufigh [92] concluded that the presence of a sufficient amount of cement improves the behavior of RE in sulfate, alkaline and acidic environments. These authors observed that 7.5 % and 12.0 % CSRE remained integrated after 1 year of exposure to the aforementioned environments, while 2.5 % CSRE disintegrated after 6 months of exposure to sulfate and alkaline environments and 9 months in an acidic environment. The sulfate solution was observed as the most destructive environment for RE materials. Luo et al. [98] also measured a reduction of RE compressive strength and cohesion in the presence of sodium chloride, sodium sulfate and calcium chloride, which was much more severe when the sodium sulfate and calcium chloride were applied simultaneously.

Finally, Narloch and Woyciechowski [95] evaluated durability of RE against frost–defrost cycles. The study concluded that a minimum of 9 % cement is needed to reach the frost resistance level required by European Standard EN 206:2013+A1:2016 [99]. According to this research, the presence of gravel in the particle size distribution of the earthen material also plays a key role in the frost resistance of CSRE.

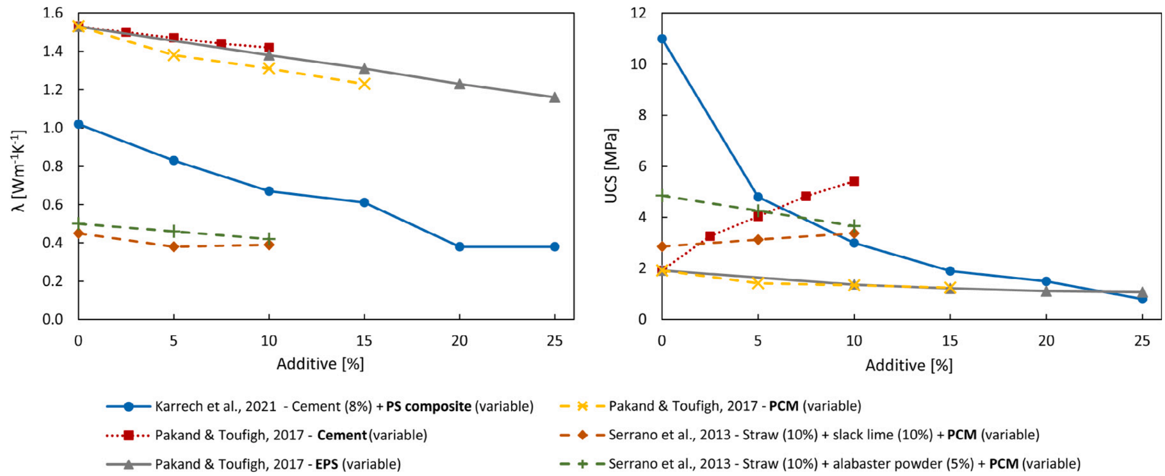


**Fig. 4.** Stabilization of RE for the improvement of thermal conductivity (left) and its effect on UCS (right). Values obtained by Karrech et al. [67], Pakand & Toufigh [60] and Serrano et al. [84].

**Table 4**
$CO_2$ emissions and embodied energy per cubic meter of RE.

| Additives | $CO_2$ emissions | | Embodied energy | |
|---|---|---|---|---|
| | Values [kg] | Ref. | Values [MJ] | Ref. |
| None (URE) | 3–9 | [60,100] | 49 | [19] |
| 2.5 % cement | 42 | [60] | – | |
| 4 % cement | – | | 280 | [9] |
| 5 % cement | 86 | [60] | – | |
| 6 % cement | – | | 400 | [9] |
| 7.5–8 % cement | 131 | [23,60] | 500 | [9] |
| 10 % cement | 179 | [60] | 630 | [9] |
| 12 % cement | – | | 750 | [9] |
| 5 % cement + 2.5 % FA | 129 | [23] | – | |
| 5 % cement + 5 % FA | – | | 155 | [19] |
| 2.5 % cement + 5 % FA | 120 | [23] | – | |
| 7.5 % FA | 106 | [23] | – | |
| 25 % FA + 6 % CCR | – | | 68 | [19] |
| 20 %vol EPS | 18 | [60] | – | |
| 10 % PCM | 1630 | [60] | – | |

## 6. Environmental and economic impact of stabilization

### 6.1. Environmental cost

One of the main benefits of rammed earth construction, and also one of the most important reasons why this technique is experiencing a significant growth over the last years, is its very limited environmental impact [1,13,15,100]. This is due to the fact that the source material is raw earth that can be frequently obtained in the construction site and which needs very low industrial processing, reducing resource and energy consumption, pollution and waste generation.

However, when the mechanical properties of raw earth are not enough to reach the required standards and so additives are included to the mixture, some of the aforementioned environmental advantages are severely reduced. Two of the main indicators that may help understanding how environmentally friendly a construction technique is are the $CO_2$ emissions and the embodied energy, and both parameters significantly increase for SRE compared to URE, as it is shown in Table 4.

When cement or other industrially manufactured products are used as stabilizers, the environmental costs increase due to the manufacturing process and the transportation distance. Actually, the embodied energy of CSRE walls linearly increases with the cement content [9]; and, for example, a 8 %-cement SRE wall implies more than 14 times the $CO_2$ emissions and 10 times the embodied energy than the same wall made with URE ( Table 4). Nevertheless, the embodied energy in CSRE is only about 15 % to 25 % of the embodied energy in common brick masonry [9].

Although other factors, such as a higher presence of clay or an increase in the required compaction level, may affect the energy consumption, their contribution to the total energy expenditure of the whole process is negligible if compared to the energy content of cement [9]. This is the reason why several recent studies aiming to develop an eco-friendly RE with greater mechanical properties than traditional URE have tried to replace cement or lime with natural stabilizers or waste materials.

Despite the fact that many studies have recently presented alternative additives as a sustainable way to improve RE mechanical characteristics, the huge differences in the methodologies applied to measure the environmental benefits (or even its absence) make it very difficult to compare the results.

One of the most common and direct ways to reduce cement consumption in RE construction is replacing it with CCR and/or FA, which significantly reduces the cumulative energy demand especially if the CCR is a waste, in which case the environmental impacts of URE and SRE are similar when local soil is not suitable by itself for construction [19]. Although the UCS is generally lower when replacing cement with CCR and FA [19,40], Kosarimovahhed and Toufigh [23] obtained that a combination between cement and alkali-activated FA could lead to a higher strength than only cement, while reducing the $CO_2$ emissions.

Other waste materials or industrial by-products have been tested, such as crushed brick and concrete from demolition, ground granulated blast furnace slag, silica fume, bottom ash or granitic residual soils [37,38,41,57]. The use of this kind of materials helps reducing the amount of industrial waste products ending up in landfills and minimizing the material and energy consumption and waste generation due to the manufacture process of stabilizers. In addition, natural fibers could be also considered as useful additives for RE, as they have been traditionally used to improve the mechanical behavior of earth constructions and have a small impact in the environmental cost [16,17].

### 6.2. Economic impact

Economic and environmental costs are strongly related when considering the stabilization of RE, as the manufacturing process of the stabilizers and the need for transportation not only reduces the sustainability of the construction technique, but also has a significant economic impact. Table 5 shows the cost of some SRE mixtures according to literature (Labor and transportation costs not included).

Analyzing the results obtained by Pakand and Toufigh [60], it is possible to observe that the ratio cost-UCS significantly decreases from

**Table 5**
Material cost per tonne of RE.

| Additive | Ref. | Cost [$/t RE] |
|---|---|---|
| None (URE) | [60] | 3.51 |
| 2.5 % cement | [60] | 4.16 |
| 5 % cement | [60] | 4.81 |
| 7.5 % cement | [60] | 5.46 |
| 7.5 % cement | [23] | 11.25 |
| 10 % cement | [60] | 6.11 |
| 5 % cement + 2.5 % FA | [23] | 10.88 |
| 2.55 % cement + 5 % FA | [23] | 10.47 |
| 7.5 % FA | [23] | 9.95 |
| 15 % EPS | [60] | 4.94 |
| 10 % PCM | [60] | 653 |

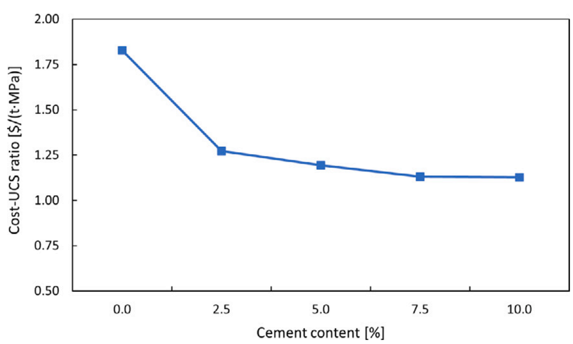


**Fig. 5.** Cost-UCS ratio of RE as a function of cement content.
*Source:* Data: [60].

URE to 2.5 % CSRE and then gradually stabilizes for increasing cement contents, reaching a value of 1.13 $/(MPa · t) (Fig. 5). This means that the increase in the cement content (and therefore the cost) leads to a greater strength gain at the beginning but this effect is much less significant for higher cement contents. It must be noted that transportation and labor costs are not included, only the cost of the materials.

Defining a single value for the economic impact of stabilizers is not possible due to the great variability in the source material, labor and transportation costs in the different countries, but more thorough investigation may help understanding the relationship between the increase in the costs and the improvements obtained for the material. This applies also to the environmental costs of RE stabilization.

## 7. Conclusions

Introducing rammed earth construction technique in new buildings implies a need to meet the requirements defined in the current construction standards, and this is the reason why stabilization is becoming increasingly important in RE construction. This study presents a review of the most relevant properties of stabilized rammed earth and their impact in the environmental an economic cost of the technique.

It has been observed that the use of cement is widespread in RE construction, making it possible to achieve high values for some of the most relevant mechanical properties, such as the compressive strength and stiffness, although its negative effect in the environmental performance of the material is frequently not taken into consideration. Recent studies, though, have evaluated the addition of alternative more eco-friendly stabilizers (fly or bottom ash, natural fibers, ...), frequently used together with cement in order to improve the mechanical behavior and reduce the environmental impacts.

Natural o synthetic fibers are often the solution if the parameter to be enhanced is tensile, flexural or shear strength, although cement and other additives are also used. Rammed earth shows low values of these properties, but they are essential in the behavior and failure of RE elements.

The main conclusions obtained in the present study are listed below:

- There exist several additives that can be included in the mixture, but cement is by far the most common and most thoroughly studied.
- The soil and water content used for SRE is similar to those used for URE, not very specific characteristics are required.
- Cement is frequently used to improve the UCS of RE, with an increase from 60 % to 250 % in most studies compared to URE. The relationship between cement content and UCS seems to be approximately linear. Cement is frequently combined with FA.
- Increasing cement contents lead to an increase in the elastic modulus, but the relationship is not so clear and some dispersion is observed.
- RE tensile strength is usually improved by the use of natural or synthetic fibers. It is observed, however, that increasing fiber contents frequently imply a reduction of the compressive strength, which is sometimes counterbalanced combining fibers and cement.
- Thermal insulation can be enhanced using thermal energy storage additives, such as EPS or PCM, reducing the thermal conductivity over a 15 %. It must be noted, however, that this kind of additives significantly worsen the mechanical behavior of RE. The enhancement of the acoustic properties of RE, on the other hand, has not be thoroughly studied yet.
- Some studies indicate that the use of cement can improve the durability of RE against water erosion, aggressive environment and frost–defrost cycles. The effect of other stabilizers on RE durability remains to be studied.
- The use of stabilizers significantly increases the environmental and economic cost of RE construction, due to the manufacturing process and transportation distances. This impacts can be reduced by replacing industrial stabilizers, such as cement, by industrial by-products (e.g. FA, bottom ash or crushed bricks) or natural additives (e.g. natural fibers).
- Standardizing the testing procedures would be essential to obtain comparable values of the mechanical parameters of rammed earth.

## Declaration of competing interest

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

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