Discover Civil Engineering

Review

A review of chemical stabilisation and fibre reinforcement techniques used to enhance the mechanical properties of rammed earth

David Thompson[1] · Charles Augarde[2] · Juan Pablo Osorio[1]

Received: 25 October 2024 / Accepted: 7 February 2025
Published online: 19 February 2025

Abstract
Rammed earth is a sustainable construction method with a lower carbon footprint and embodied energy compared to traditional materials like steel and concrete. However, its lower mechanical properties when compared to these forms of construction make it vulnerable to seismic forces. This paper reviews the published literature on enhancing rammed earth's mechanical properties through both chemical stabilisation and fibre reinforcement, with a focus on reusing waste materials. The effectiveness of these techniques are highlighted by comparing experimental results with minimum specifications taken from relevant guidelines and standards for building rammed earth structures in seismic zones. These findings demonstrate that chemical stabilisation and fibre reinforcement can improve rammed earth's mechanical properties, ensuring it meets these minimum specifications thus making it a viable form of construction in areas with seismic activity.

Keywords Rammed earth · Stabilisation · Fibres · Reinforcement · Seismic

1 Introduction

Rammed earth (RE) is a form of earthen construction where moistened earth is compacted in layers between removable formwork to form the walls of a building. Earthen construction is a more sustainable form of construction in certain forms, therefore embracing it may help decrease our reliance on CO_2 intensive forms of construction. CO_2 emissions associated with cement production, a key component of concrete, represent approximately 8–9% of global anthropogenic CO_2 and 2% of global energy use with some research predicting a 50% increase in annual production of cement by 2050 [1].

Traditional forms of construction, such as steel and concrete, have been in use for a long time, with much research carried out to fully understand their material properties which allows engineers to have confidence in their structural performance. RE however can have different material properties, depending on the type and make-up of the soil used. Research is needed to better understand the structural behaviour of RE. This knowledge would give the construction industry greater confidence in using it as an alternative to traditional forms of construction currently in use.

As can be seen in Fig. 1, earthen construction (including RE) is often used in areas where moderate, high and very high seismic activity occurs and a number of earthquakes have occurred in areas where rammed earth is prevalent such as Iran in 2012, Pakistan in 2013, Afghanistan 2015 and Nepal in 2015. The low strength of RE in compression,

✉ David Thompson, david.thompson@tudublin.ie; Charles Augarde, charles.augarde@durham.ac.uk; Juan Pablo Osorio, juan.osorio@tudublin.ie | [1]School of Transport and Civil Engineering, TU Dublin, City Campus, Bolton Street, Dublin 1, Dublin D01 K822, Republic of Ireland. [2]Department of Engineering, Durham University, Durham, UK.

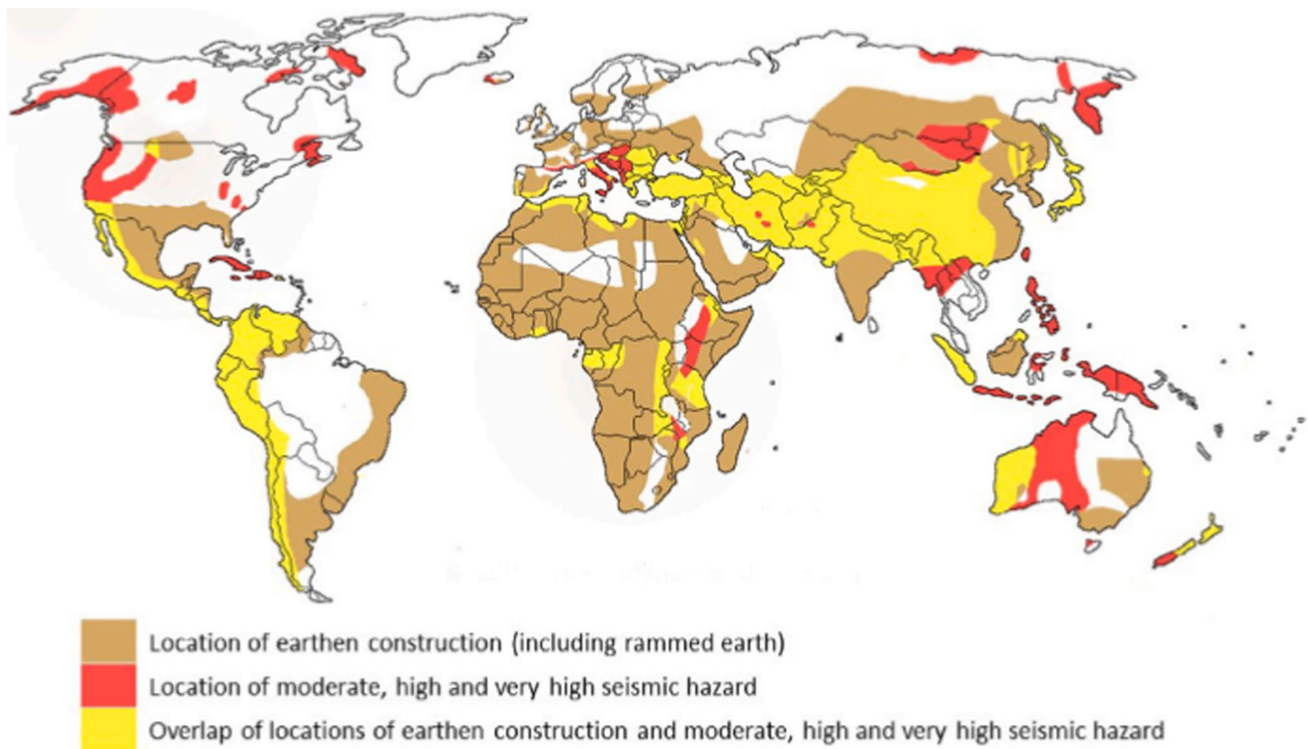

Fig. 1 Location of earthen construction and seismic hazards [2]

bending, and shear makes buildings constructed with RE more susceptible to collapse when subjected to seismic forces, compared to traditional construction methods that employ modern reinforcement techniques [2].

Perić et al. [3] discusses the relation between certain physical characteristics of RE, including particle size distribution, moisture content and dry density, with unconfined compressive strength (UCS), shear strength and Young's modulus. These properties, with the addition tensile strength, are the focus of this review as they are key material properties when characterising the mechanical behaviour of the material.

The most common material property observed in this review was the UCS. As there is no standardised test procedure for obtaining this value, different studies have utilised different methods. Ávila et al. [4] states that ASTM D 1633 [5] Standards for Compressive Strength of Soil Cement Cylinders can be used while other studies have utilised procedures derived from other standards for cement mortars, masonry and concrete testing [3] to determine the UCS of rammed earth. It has also been observed in this review that various cylindrical sized samples are also used. This non-standardised approach leads to a wide variety of sample sizes and loading methods across published literature. Perić et al. [3] mentions that different shapes and dimensions of the same concrete specimens can result in different UCS and that studies by Maniatidis and Walker [6] and El-Nabouch [7] have shown similar results for RE, in that smaller samples sizes can result in higher UCS values.

The most common methods for improving the material properties of RE include stabilisation and fibre reinforcement. The stabilisation of soil generally refers a soil which has addition materials added, in order to improve its mechanical properties. These materials can be chemically active, e.g. cement or lime, or non-chemically active materials such as waste plant fibres. In many papers, the term stabilisation is used for adding any materials to RE, while others use other terms such as reinforcement when discussing adding non-chemically active materials. In order to clearly differentiate between the two processes, the terms chemical stabilisation will be used when specific chemicals are used and fibre reinforcement for when fibres are used. Studies which used reinforcement bars in rammed earth were also excluded.

Therefore, the aim of this study is to review the current state of the art knowledge relating to rammed earth construction and the methods used to improve its material properties to help improve its resistance to seismic forces. To achieve this, the following research questions are presented.

Q1—What are the most effective methods at enhancing mechanical properties of rammed earth?
Q2—Can these enhanced material properties adequately strengthen RE in order to make it suitable for use in seismically active zones by meeting minimum material property specifications in codes and standards?

2 Search methodology

2.1 Systematic literature review

The PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) of revising was utilised. This method combines keyword searches and uses a four-stage method of reducing the number of articles to be selected for the final review, e.g. selection of papers from databases, review for eligibility and detailed analysis [8].

Keyword searches were used to identify articles across two scientific databases, Science Direct and Web of Science. Initial searches used the terms "Earthen Construction" AND "Stabilisation" and "Earthen Construction" AND "Fibres". These terms were selected to ensure studies relating to other types of earthen construction, other than rammed earth, were considered. Another search using the terms "Rammed Earth" AND "Fibre" and "Rammed Earth" AND "Stabilisation" were utilised in order to focus the search further. As this study is focusing on specific material properties, the following combined word searches were utilised; "Rammed Earth" AND "shear strength", "Rammed Earth" AND "compressive strength", "Rammed Earth" AND "Bending Strength", "Rammed Earth" AND "Flexural Strength", "Rammed Earth" AND "Young's Modulus". Checks for variations on spelling were also carried out and no references were missed due to different English spelling. Results included for this review included conference papers and journal articles. Books were excluded as they generally provide information on construction guidelines as opposed to state-of-the-art research. There was also no limit on date of publication.

Next the eligibility for including or excluding articles was assessed. Articles were reviewed in order to identify if the studies were related to this review's aims. This was done by reviewing article titles and abstracts to ascertain the scope and content of each article. Inclusion criteria specified that articles can be research articles, review articles, in English and published up until 2024. Exclusion criteria included studies in other languages other than English, duplicated studies, articles with no links to research terms. Once articles were identified for use in this review, a comprehensive review of the articles was carried. This involved reading each paper in detail to understand its scope and ascertain if specific information needed for this review was present, i.e. details on material properties and experimental works relating to rammed earth. Finally, a second detailed review was carried out to identify any duplicates and again to ascertain their relevance to this review. The results of the search strategy in the selected databases are shown in Table 1 and the results after applying the PRISMA method are shown in Fig. 2.

After applying the PRISMA method, 114 papers were identified for use in this study.

Table 1 Search results from databases using key word combinations

Title, Abstract, Keywords	Science Direct Papers found	Web of Science Papers found
"Earthen Construction" AND "Stabilisation"	281	7
"Earthen Construction" AND "Fibres"	233	3
"Rammed Earth" AND "Shear strength"	122	27
"Rammed earth" AND "Compressive strength"	384	174
"Rammed Earth" AND "Bending strength"	25	4
"Rammed Earth" AND "flexural strength"	133	17
"Rammed Earth" AND "Young's modulus"	120	8
"Rammed Earth" AND "Fibre"	329	13
"Rammed Earth" AND "Stabilisation"	475	18
TOTAL PAPER FROM DATABASES	2102	271
Overall total	2373	

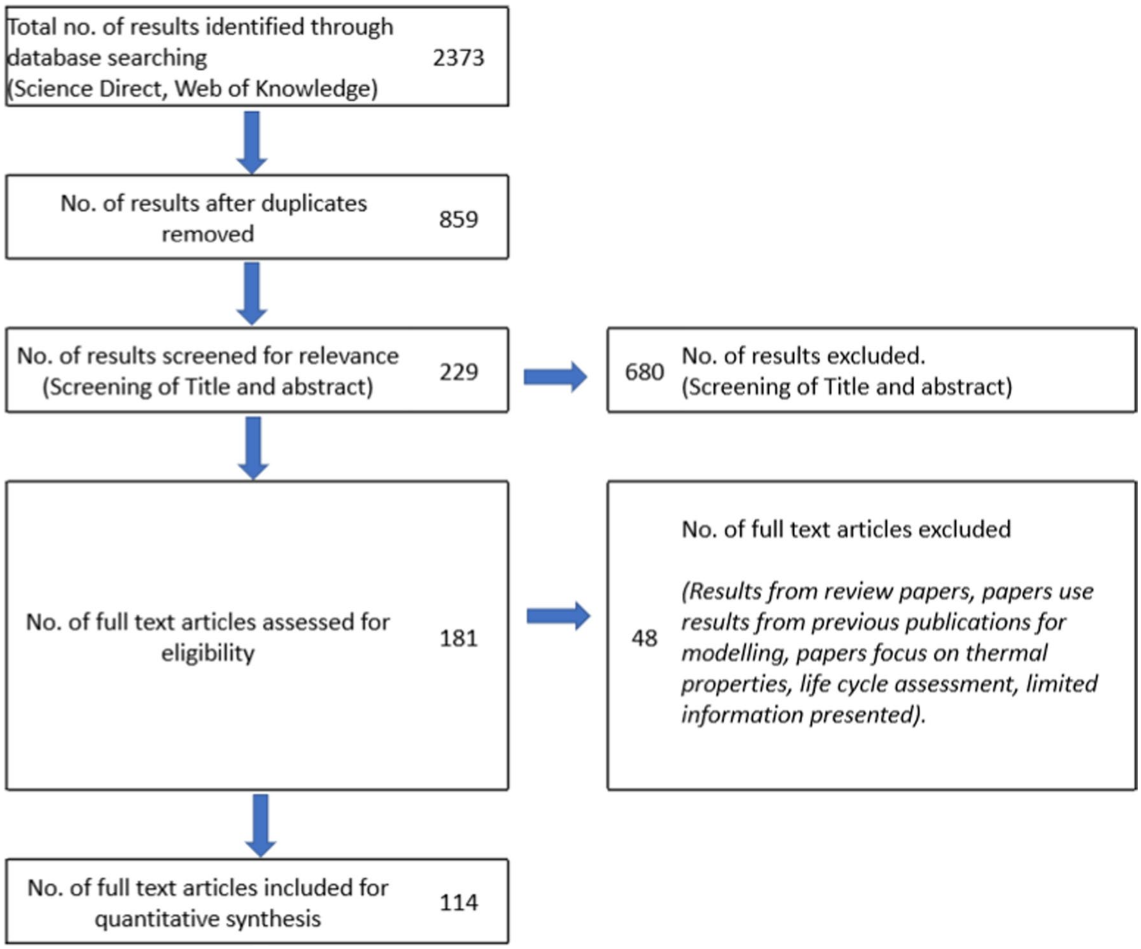

Fig. 2 Results after applying PRISMA method

3 Review of current literature

3.1 Background information

As previously explained, chemical stabilisation of soil refers to the addition of a chemically active agent which reacts with the soil with the aim of enhancing certain mechanical properties. This section describes various methods of chemical stabilisation and fibre reinforcement used in earthen construction. Other forms of earth construction, such as adobe, cob and earth bricks/blocks, were also considered. Since similar methods are used for enhancing their mechanical properties, the results of these studies can inform the chemical stabilisation and fibre reinforcement techniques used for RE. In order to determine mechanical properties of earthen construction, experimental works need to be carried out. Experimental tests include unconfined compression tests, bending tests, tensile and shear strength tests as well as determining properties such as the Young's modulus. As there are no standards relating to the testing of earthen construction, test methodologies vary from study to study. These variations include different specimen sizes and shapes. Some studies follow experimental tests for masonry specimens while other utilise those used to test for determining geotechnical or concrete mechanical properties. While stabilisation is important, many studies have focused on testing unstabilised soil / RE. In many cases these results are part of a wider study on earthen construction or rammed earth which generally looked to improve specific mechanical properties over the control or unstabilised earthen samples [9–35].

3.2 Chemical stabilisation

Stabilisation is a common method for enhancing the mechanical properties of soil and is proven as an effective method for use in road construction projects to enhance the strength and therefore the load bearing capacity of the soil on which the road is to be constructed [36]. These principles can also be applied to earthen construction. The addition of stabilisers to the soil used in earth construction facilitates improved binding of soils and aggregates which can result in enhanced mechanical properties. A wide range of chemical stabilisers are used such as cement, lime waste fly ash and enzymes.

In terms of the percentage of stabilisers used in earthen construction, values wary from study to study, with most testing different percentages by weight of the soil. In the papers reviewed here, the amount of stabiliser used ranged from 2% up to 20%, depending on stabiliser type. Tripura et al. [33] produced RE specimens and found that adding 10% cement content by weight, achieved the criteria for UCS as set out by various standards. UCS values increased with higher cement contents with 10% cement achieving 4.15N/mm^2 compared to 4% cement content achieving 1.35 N/mm^2. They also observed that cured samples achieved UCS values two times greater than non-cured samples.

Cement is the most common chemical stabiliser identified across the literature. Studies investigating cement stabilisation usually create test specimens with varying percentages of cement (by weight) to determine the optimum cement content. The addition of cement has been proven to enhance the various material properties of RE samples such as compressive, bending and shear strength, [37–62]. For example, Walker and Dobson [47] found that RE stabilised with cement produced higher UCS values across different soils and also noted cement content of RE can affect the pullout bond resistance of rebar in RE. Ciancio et al. [13] found that soil stabilised with 4–5% cement by weight produced satisfactory UCS values (3.14–12.14 N/mm^2) compared to unstabilised rammed earth (URE), (0.32–0.86 N/mm^2) thus highlighting the positive effect cement can have on enhancing certain mechanical properties of RE. A number of studies have stated that approximately 5–10% stabiliser content achieves optimum results in terms of strength gain, with 10% content by weight being the most common percentage, [14, 17, 19, 27, 38, 39, 46, 53, 61, 66]. Stabiliser contents above this may have enhanced material properties but the benefits of using a "green" construction material like earth, will decrease as certain stabiliser contents are increased.

Among the studies that examined cement stabilisation, some interesting findings were discovered. Consoli et al. [45] produced RE specimens with increasing cement contents of 3–9%, with specimens with 9% cement content achieving the highest UCS values. They also identified relationships between strength with porosity/cement ratio and curing periods which enabled predictions of UCS to be made. This relates to other studies who have looked at ways to predict UCS values. One study focused on using computer programmes to predict RE strength [40, 41, 63] while Bui et al. [50] compared laboratory test results to those from the Schmidt hammer test, producing specific calibration curves for RE in the process. As previously mentioned, varying shapes and dimensions of test specimens can result in different UCS values. Therefore, developing reliable, non-destructive methods to predict the mechanical properties of earth construction would be beneficial for future research. The addition of cement has also been observed to enhance the same properties in other forms of earthen construction, e.g. adobe [64] therefore ways of predicting material strength in other forms of earth construction may be possible.

Lime is also a common substance used to stabilise RE and other forms of earthen construction. Many studies refer to lime differently, e.g. air lime, hydrated lime, hydraulic lime, natural hydraulic lime or quicklime. Limestone is a naturally occurring rock composed of calcium carbonate. This can then be heated to 900–1000 °C in a kiln to form calcium oxide which is the lime powder used in the stabilisation process. The addition of lime was again shown to enhance compressive strength of RE samples [11, 15, 20, 21, 30, 49, 65]. Studies showed that the effect of lime only stabilisation on UCS values is not as significant as using cement. For example, Koutous et al. [20], produced specimens stabilised with 4% lime by weight resulted in a UCS of 2.15 N/mm^2, compared to unstabilised specimens which achieved 2.06 N/mm^2. Cement only stabilised RE specimens achieved a UCS value of 3.24 N/mm^2, indicating that lime alone is not as effective as cement at enhancing UCS. This leads to studies investigating lime / cement mixes for stabilisation purposes. In these studies, lime was incorporated as a means of reducing the carbon footprint of cement stabilised RE samples while maintaining the benefits of the cement stabilisation. Varying mix ratios were tested with results showing certain lime/cement mixes can also enhance material properties with UCS being the most commonly tested [13, 17, 66, 67]. For example, Hallel et al. [17] also conducted studies on various cement/lime RE mixtures and found that unstablised RE produced a UCS of 1.3 N/mm^2, while those stabilised with 2% cement and 4% lime gave a UCS of 3.71 N/mm^2 and a 4% cement + 4% lime mix gave a UCS of 4.84 N/mm^2. This compared to the cement only specimens which had a UCS of 4.3N/mm^2.

The use of waste materials as a form of stabiliser in earthen construction has also been investigated in a number of studies. A common method incorporates fly ash, which is the fine particulate that is collected in the filters of the chimney stacks as part of waste incineration. This material is usually mixed with an alkaline activator which facilitates the enhanced reactivity of fly-ash which helps bind together the soil aggregates, thus improving the strength of RE, [68]. The addition of fly ash, along with other stabilisers has shown increased compressive strengths compared to unstablised earthen blocks [69–71] and RE samples [68, 72–82]. Similar enhancements of mechanical properties have also been found using slag, which is a waste by product from steel production, as a stabiliser [22, 32, 83]. For example Lui et al. [22] also used slag as a stabiliser by adding 25% by weight of soil of slag to RE samples. They achieved an average UCS value of 6.2 N/ mm^2 for the stabilised samples compared to 2.9N/mm^2 for unstabilised samples.

Another method of stabilisation that has been researched in recent years involves utilising enzymes in the stabilization process. An example of this were studies looking at enzymatic induced calcite precipitation (EICP) using plant derived urease from the fine powder of soybeans. These studies showed that earthen samples, stabilised with EICP had enhanced properties compared to unstabilised samples, in terms of UCS and durability [84–86]. In another study an enzyme called TerraZyme, which is formulated using sugarcane molasses, was mixed with lime and cement. The results showed that the presence of TerraZyme enhanced the stabilisation effect of conventional stabilizers when used alone or in combination with each other [67]. Biopolymers, such as guar guar gum and xanthan gum have also shown promise in stabilising soils by enhancing UCS, Young's modulus and durability [4].

3.3 Fibre reinforcement

Fibre reinforcement is a common method used to improve the mechanical properties of RE. Laborel-Préneron et al. [87] conducted a review of plant aggregates and fibres for use in earth construction and grouped the different types of fibres in eight categories, noting that the most common plant fibre used were types of cereal straw, including wheat straw, barley straw, oat straw. For the purposes of this review, fibres are classified as natural fibres (i.e. organic materials) or non-natural fibres (i.e. inorganic materials) as per Hejazi et al. [88], with fibres being added to unstabilised and/or stabilised earthen samples.

In the studies investigating the use of natural fibres in RE, it was observed that results from the stabilised RE and fibres produced higher UCS results than unstablised RE with fibres [14, 26–29, 89–92]. Similar findings were also observed in studies looking at other forms of earthen construction such as adobe and earth blocks [93–104]. Other material properties were also shown to improve with the addition of natural fibres, including shear strength [105, 106] and tensile strength [96, 99, 104, 107, 108]. In relation to tensile strength, another important factor that has been identified in the literature is the pullout strength of the fibres from earthen materials. The tensile strength of the soil has been shown to increase with increased fibre contents which has been attributed to the pullout resistance of fibres and the earth [107, 108]. A specific example of this can be seen in a study by Sri Bhanupratap et al. [91]. They carried out tests on cement stabilised RE, in order to investigate bond strength of coir fibres. Mixes with cement contents of 7% and 10% along with 0.5%, 1%, 1.5% and 2% fibre content by volume were cast and tested at 28 days. Optimised percentages of 1% fibre content with 10% cement content produced highest values for UCS of 6.87 N/mm^2. The study concluded that the addition of coir fibres increased the ductility and post peak carrying capacity of the material thus avoiding catastrophic shear failures when tested under compression. They also found that energy absorption capacity of cement stabilised RE also increased by 2–5 times with the addition of coir fibres. Fibres have been shown to enhance the bending strength of earthen materials and helped limit crack propagation as the use of fibres induces a bridging effect between the cracks. In such cases the load can be maintained as long as the fibres do not pullout of the earthen material [94, 95, 98, 109]. Corbin and Augarde [14] also demonstrated the benefits of fibres where they tested waste wool fibres and showed that for specimens without any wool, the load dropped steadily from peak load until the end of the test, whereas specimens with wool showed that the load dropped approximately 60–80% from the peak and then remained constant at that force +−20%.

Inorganic fibres such as waste textile fibres, polypropylene fibres and crumb rubber, have also demonstrated an ability to enhance UCS [26, 27, 35, 89] and shear strength [106] of earthen materials. Wang et al. [110] demonstrated that the California bearing ratio (CBR) of a London clay soil, can be enhanced with the addition of polypropylene fibres, thus increasing the soil bearing capacity.

In the review conducted by Laborel-Préneron et al. [87], they found that fibre contents varied from 0.2 to 4% by weight for adobe, 1.5–12.2% by weight in compressed earth blocks (unstabilised) and from 0.06 to 40% for stabilised earth blocks. Rammed earth was not reviewed in detail in that paper, however from the literature found for this review, fibres contents for rammed earth ranged from 0.25 to 5% by weight [14, 26–29, 31, 35, 89–92]. Mabrouk et al. [24] were outliers in their use of fibres, employing a hemp fibre content of 25% by weight.

In all the aforementioned studies, the enhancement in the specified mechanical properties was only true up to a certain percentage of fibres being added. Each study identified a percentage at which fibre content had a negative effect on the properties under investigation. For example, Sri Bhanupratap et al. [91], found that the UCS increased by 10–30% by adding 1% coir fibres by weight, achieving a UCS value 6.87N/mm^2. Percentages of fibres greater than this up to 2% and lower, down to 0.5% resulted in lower UCS, indicating that 1% by weight was the optimum value for increasing UCS. Corbin and Augarde [14] also made similar findings where they inferred that there is a critical percentage of wool fibre which can be added to cement stabilised RE, at which point no further increase in UCS will be achieved. Other studies found upper limits on fibre content of 0.8% for coconut fibres [29] and 0.25% for cornsilk fibres [92].

4 Comparison of findings with standards and codes

Thompson et al. [2] produced a review of building codes and standards for rammed earth construction, and of the ten which has seismic provisions, only three specified minimum values in relation to material properties, e.g. Australian Earth Building handbook—HB 195–2002 [111], New Zealand Standard—NZS 4297:1998 [112] and New Mexico Building Code – 147.7.4 NMAC (2006) [113]. These material properties specifications are shown in Table 2.

In order to ascertain if the stabilisation and fibre reinforcement methods reviewed in the previous section, are suitable for construction, values reported in the aforementioned studies will be compared to minimal material properties specified in these RE building codes and standards. While the previous section looked at stabilisation and fibre reinforcement methods for various types of earthen construction, this section will specifically focus on values pertaining to RE. This is to ensure an accurate comparison to the minimum specifications in Table 2 which relate to RE specifically.

Figure 3 show the results from the selected studies showing the maximum recorded UCS values of unstabilised rammed earth, compared against the minimum specifications presented in Table 2.

From Fig. 3 it can be seen that the majority of studies carried out on unstablised rammed earth, which were a mix of engineered soil and natural soils, reached the minimum UCS specifications of HB 195–2002 and NZS 4297:1998. Using NMAC 14–7-4:2016 reduced the number of studies that achieved the required UCS. Only two studies [14, 31] achieved UCS values which did not meet any of the minimum specifications. One of these, Sharma et al. [31] used a soil classified by the Indian Standards as a clay of low compressive strength, hence the particularly low UCS values achieved compared to the other studies. Overall the majority of the studies would be suitable for use in rammed earth construction based on the UCS values.

Figure 4 shows the maximum UCS values obtained for stabilised rammed earth samples using cement only (blue), lime only (magenta) and a cement/lime mix (grey). For the studies using cement only, Consoli et al., [45] failed to meet the specifications of NMAC 14-7-4:2016 and Sharma et al., [31, 45] failed to meet all minimum UCS values as specified in Table 2. All other cement only stabilised RE achieved the specified UCS values. For those studies that utilised lime only, results were more varied in that three studies [11, 49, 114] meet the specification of HB 195-2002 and NZS4297:1998 but failed to meet those of NMAC 14-7-4:2016, whereas [15, 20, 65] met the minimum specifications of those in Table 2, however in general it can be seen that lime only stabilisation failed to achieve the high UCS values obtained when using cement only. Four studies were identified that utilised a cement / lime mixture with the aims of using a stabiliser while

Table 2 Material properties specified in selected construction guideline publications

	HB 195-2002 [111]	NZS 4297:1998 [112]	NMAC 14-7-4:2016 [113]
UCS (N/mm^2)	0.4–0.6^{fc}	0.5	2.07
Bending strength (N/mm^2)	0.5–2.0^{fc} or 0.0	0.1	–
Young's Modulus (N/mm^2)	500	300*UCS	–
Shear strength (N/mm^2)	0.0[1]	0.0–0.08	–

–, not mentioned

fc Design value for characteristic compressive strength

[1]Taken as 0 unless tested

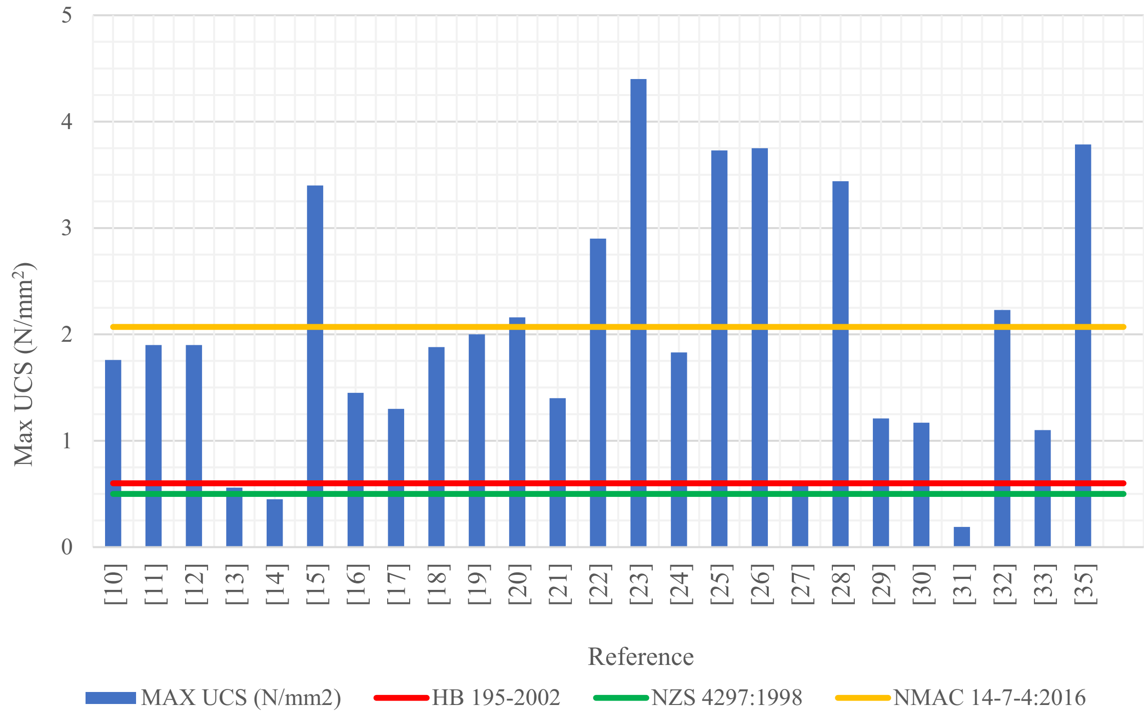

Fig. 3 Maximum UCS of URE plotted against minimum specifications from Table 2

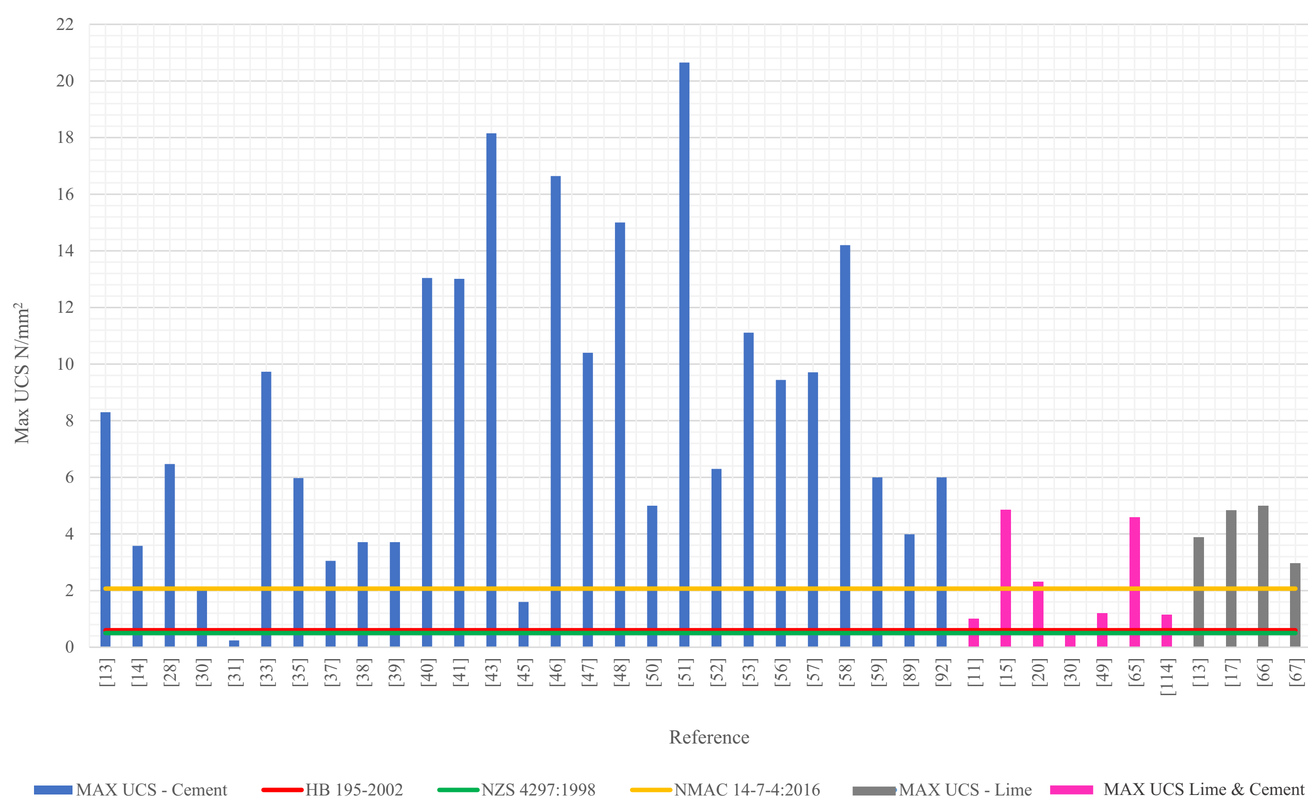

Fig. 4 Maximum UCS of stabilised rammed earth compared to minimum specifications in Table 2

trying to reduce the amount of cement needed. It can be seen that only Ramezakanpour et al. [30] failed to meet any of the minimum specifications where the remaining studies [13, 17, 66] exceeded the minimum UCS values. Results indicate that the cement/lime mix does not produce the same high strength values of cement only stabilisation but can achieve comparable results to lime only stabilisation, depending on the properties of the soil being used.

Figure 5 shows the UCS achieved for rammed earth utilising waste materials as a stabiliser. The composition of the stabilisers in terms percentages and types of materials used, (i.e. fly ash, rice husk ash, lime, cement and slag), varied from study to study so a direct comparison in difficult to make. Just over half the studies achieved UCS values which met the minimum specifications set out in Table 2. It does show that using waste materials such as fly ash can achieve high UCS values which would make it suitable for use in rammed earth construction in seismically active zones.

Figure 6 shows the maximum UCS values from the selected studies for RE specimens utilising fibre reinforcement. The studies presented here were a mix of RE with fibre only reinforcement (blue) and cement stabilised RE with fibre reinforcement (orange), where studies tested one or both scenarios. The amount of fibres added were calculated as a percentage of the weight of the RE samples. For the studies using cement as a stabiliser, cement contents of between 2.5 and 12% were used with 10% cement being seen as the most common values for optimum percentage in terms of achieving the highest UCS. As has been the case previously, the specimens using cement as a stabiliser and fibre reinforcement have higher UCS values than those without cement. Three studies [24, 31, 90] obtained UCS values below the minimum specifications in Table 2. Sharma et al. [31] was identified in previous sections as using soil known to have a low UCS. Mabrouk et al. [24] also has a low UCS which maybe explained due to the percentage of fibres used. In this study 25% by weight of hemp fibres were used to reinforce the RE. All other studies using fibre reinforcement used values between 0.8–5% by weight, with 1% by weight being found to be the optimum percentage at which UCS values can be improved. Percentages higher than 1% were found to have lower UCS values.

Figure 7 shows the results of bending strength tests carried out on various configurations of RE samples including fibre reinforced unstabilised RE (FRURE), stabilised and fibre reinforced RE (SFRRE) and stabilised RE (SRE). In these studies cement was used as the stabiliser. The minimum values for bending strength as specified in Table 2 by HB 195-2002 and NZS4297:1998 are shown. For HB 195-2002, minimum bending strengths were specified as between 0.5 and 2.0 N/mm^2. For this chart, the lower value was chosen as it was close to the value specified in NZS4297:1998 of 0.2 N/mm^2. Only two studies produced results that failed to meet HB 195-2002 specifications, however all results met the specifications in NZS4297:1998. Interestingly, the lowest bending strength was observed in an URE sample, while all other samples

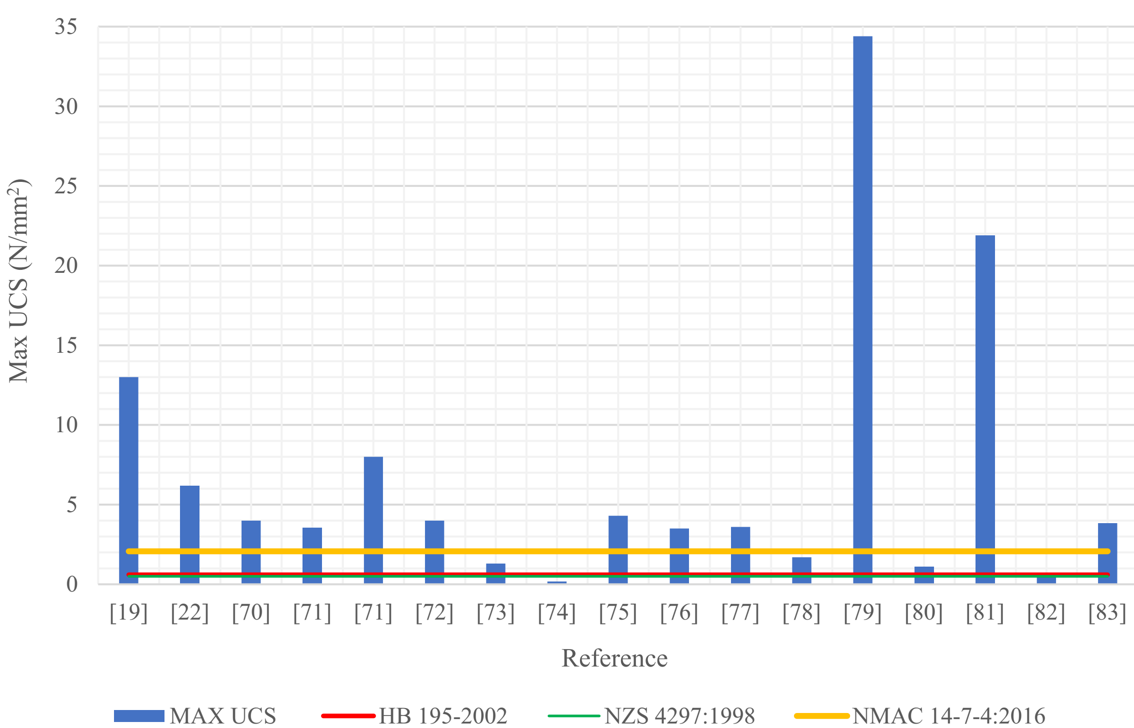

Fig. 5 Maximum UCS for RE stabilised with waste materials

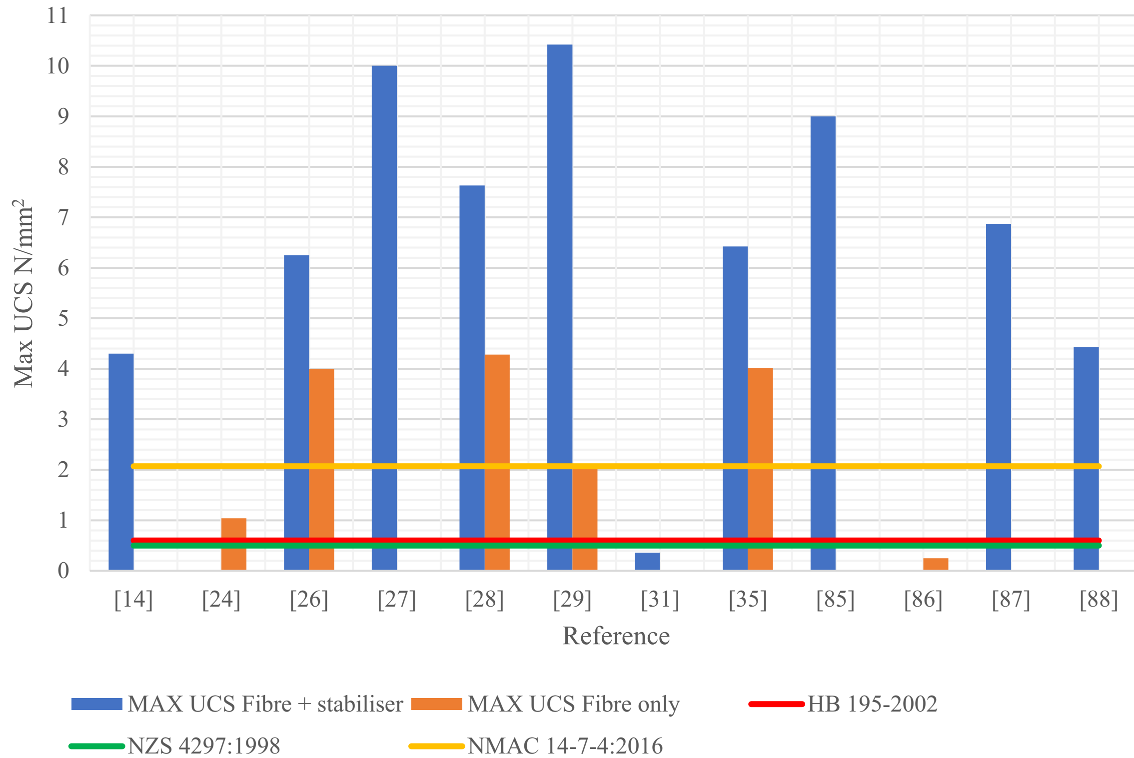

Fig. 6 Maximum UCS for RE with fibre reinforcement

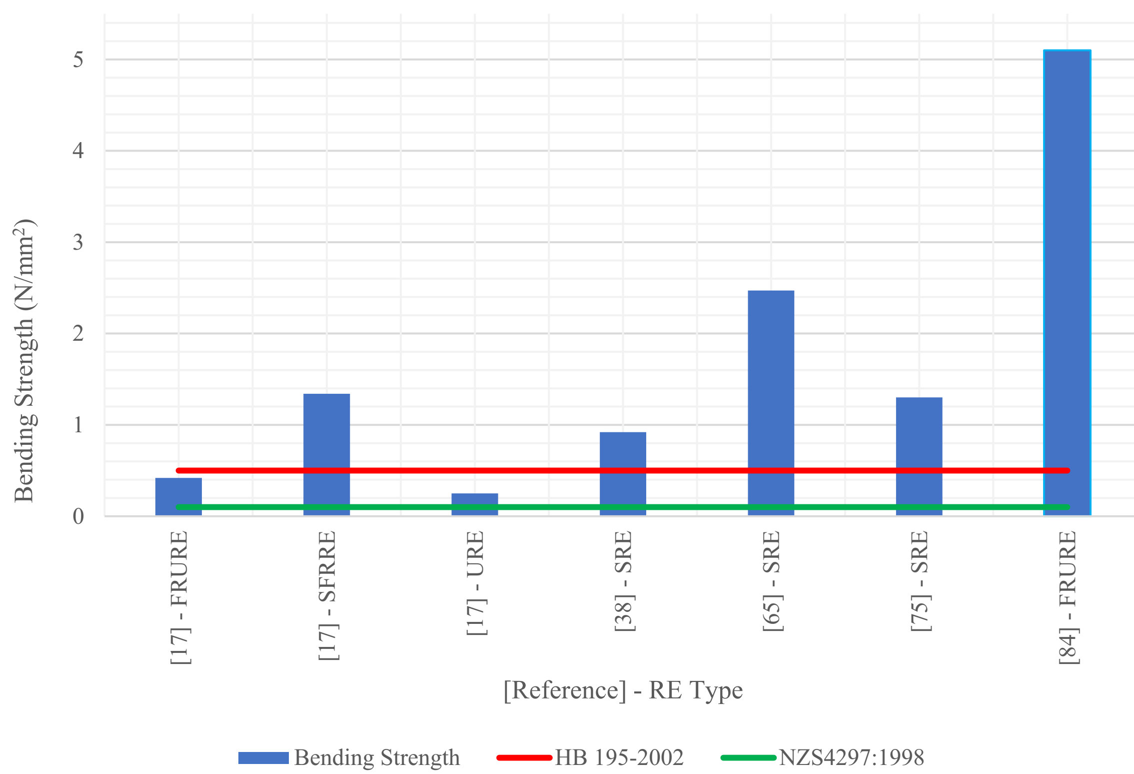

Fig. 7 Bending strength from published papers compared to minimum values in Table 2

incorporated some form of stabilisation or fibre reinforcement which indicates the positive effect these enhancements methods can have on bending strength.

Figure 8 shows the results of shear strength tests of rammed earth specimens. For determining shear strength, various experimental methods were used, including Mohr Coulomb criterion which defined shear strength as a function of various geotechnical factors including cohesion, normal stress and friction angle, [11, 59, 115], diagonal compression test [25, 116–118], triplet test [60, 61] and direct shear test utilising the shear box test procedure, [119]. Plotted on this chart is the minimum shear strength as specified by NZS 4297:1998 which shows that all results met the minimum requirement of 0.08 N/mm^2. Lepakshi et al. [59] and Corbin and Augarde [14] achieved the highest shear strengths of 3.18 N/mm^2 and 2.2 N/mm^2 respectively. Both used cement as a stabiliser which like results from bending and compressions tests, produced higher strengths compared to unstabilised specimens.

Figure 9 shows a comparison of tensile strengths of RE. There is no minimum tensile strength specified in the codes and standards in Table 2 despite it being an important factor in structural engineering. Values observed range from 0.03N/mm^2 for lime stabilised RE (LSRE) and 0.89N/mm^2 for fibre reinforced cement stabilised RE (FRCSRE). It can be seen that the samples that contained fibres had the higher tensile strengths compared to those without fibres, which would indicate that the addition of fibres can improve the tensile strength of RE.

Figure 10 shows the values of Young's Modulus reported in a number of studies. This property is reported in high number of studies, as opposed to bending or tensile strength as it usually measured in conjunction with UCS testing. HB 195–2002 specified a Young's modulus of 500 N/mm^2 and as can be seen in Fig. 10, only four studies achieved this minimum value, which indicates that RE has inherent weaknesses in this area. The maximum value observed was 950 N/mm^2 for a cement stabilised RE sample (CSRE) [11] and the lowest was 40 N/mm^2 for a URE sample [17].

From the information presented on the various material properties, the following observations can be made:

i. UCS values for unstabilised rammed earth ranged from 0.19 to 4.4 N/mm^2 with the average UCS being 2.02N/mm^2.
ii. UCS values for stabilised rammed earth ranged from 0.5 to 20.65 N/mm^2 with an average UCS being 7.06 N/mm^2.
iii. UCS values for unstabilised rammed earth with fibres ranged from 0.25 to 4.28 N/mm^2 with an average value of 2.60 N/mm^2.
iv. UCS values for stabilised rammed earth with fibres ranged from 0.36 to 10.42 N/mm^2 with an average UCS being 6.57 N/mm^2.

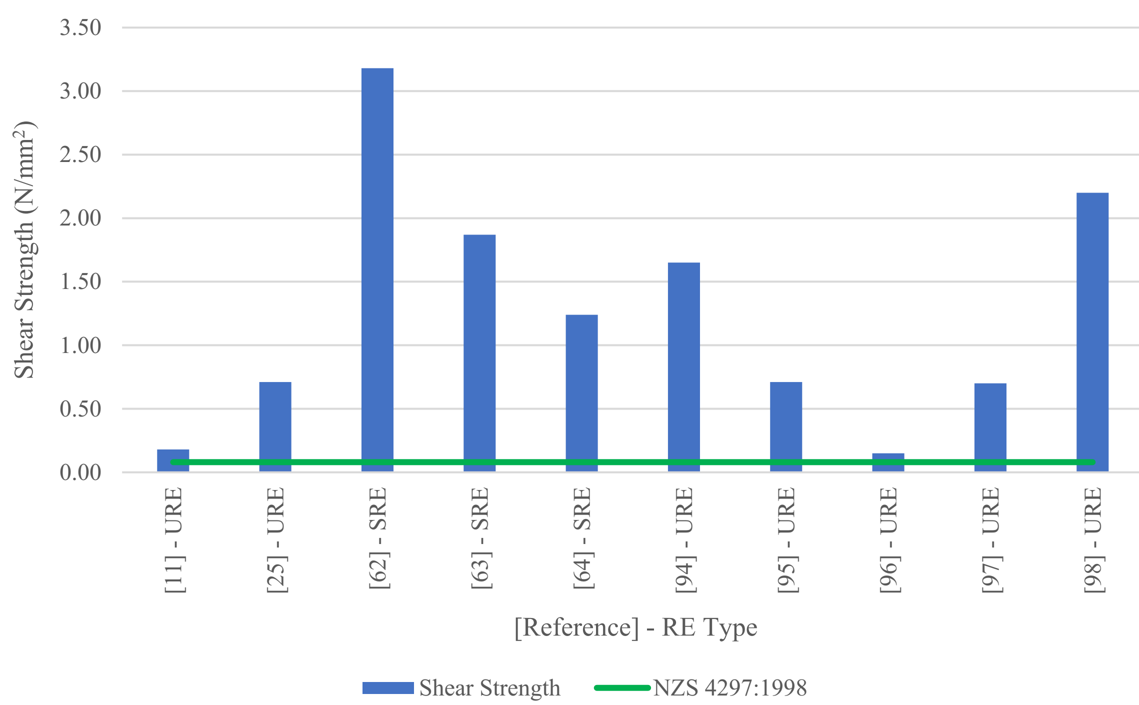

Fig. 8 Shear strength from published papers compared to minimum values in Table 2

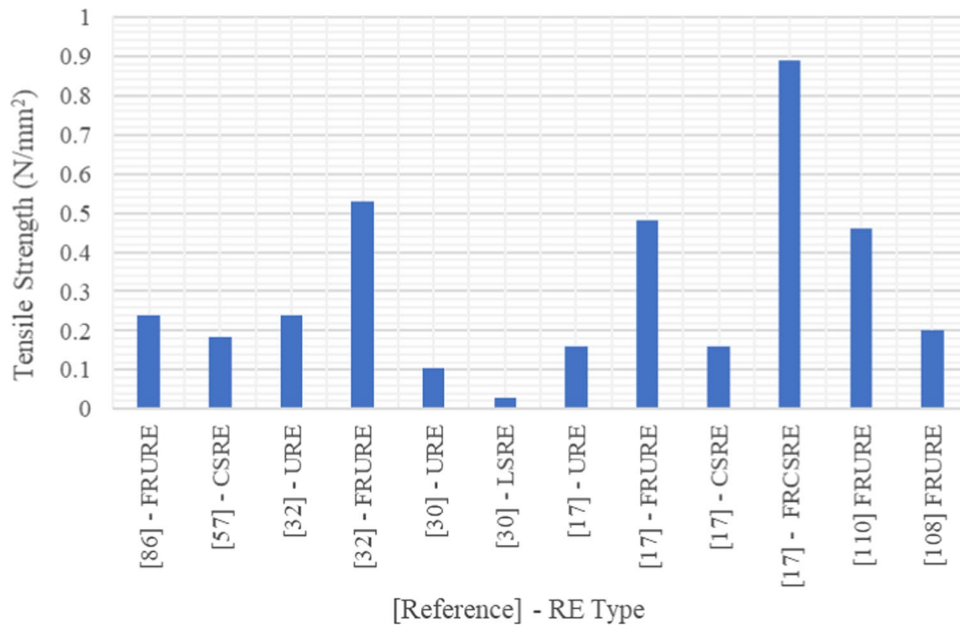

Fig. 9 Comparisons of tensile strengths of RE

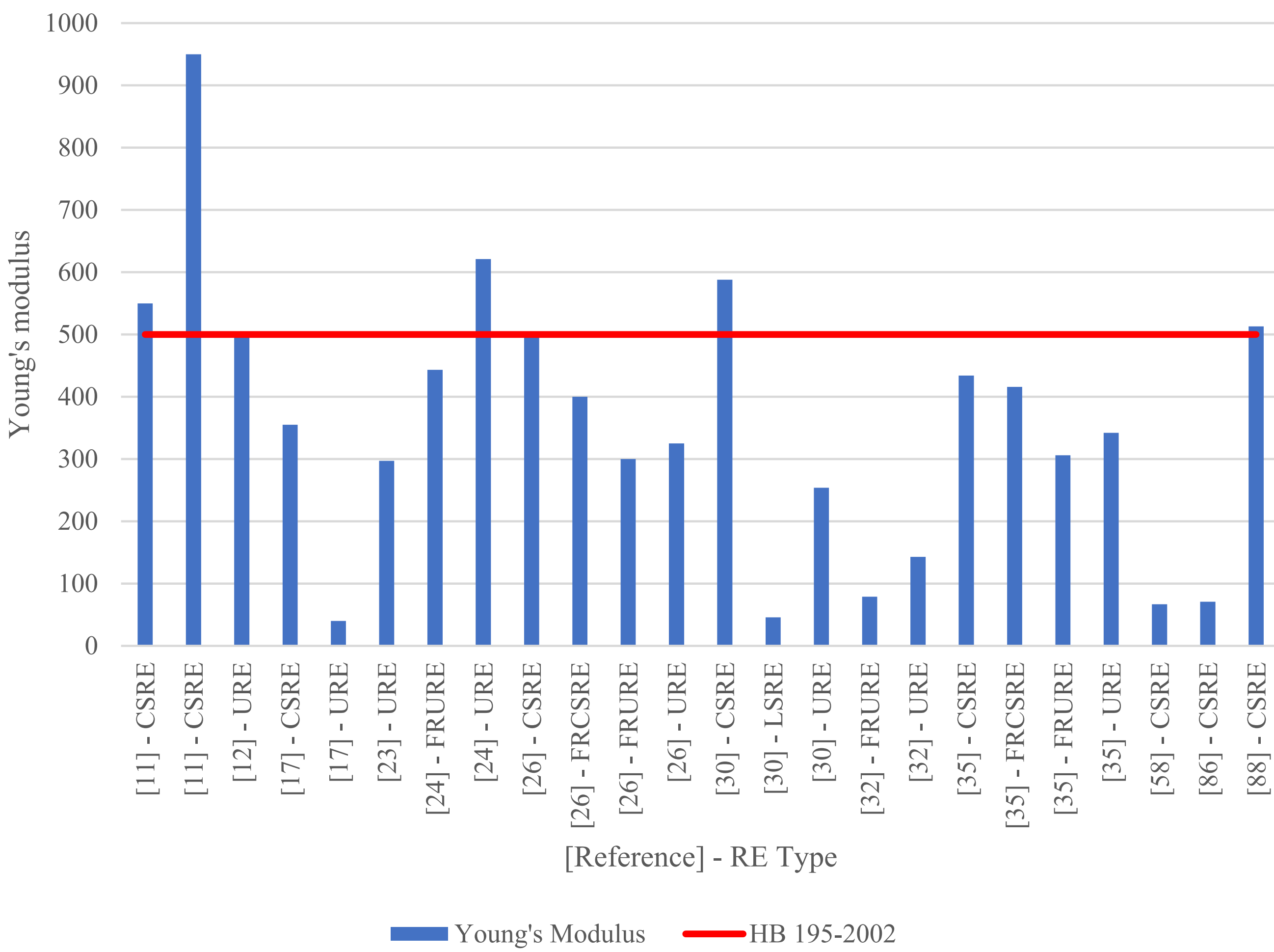

Fig. 10 Young's Modulus of RE compared to minimum specification in HB 195-2002

v. Bending strength values for all types of rammed earth ranged from 0.42 to 5.1 N/mm^2 with an average value of 1.69 N/mm^2.
vi. Shear Strength values for all types of rammed earth ranged from 0.18 to 3.18 N/mm^2 with an average value of 1.26 N/mm^2.
vii. Tensile strength values for all types of rammed earth ranged from 0.03 to 0.89 N/mm^2 with an average value of 0.302N/mm^2.
viii. Young's Modulus values for all types rammed earth ranged from 40 to 950 N/mm^2 with an average value of 356N/mm^2.
ix. The majority of studies met the minimum specifications from Table 2 for UCS, shear strength and bending strength.
x. Optimum fibre content for the different types of fibres was approximately 1% with higher percentages of fibres resulting in a downward trend in terms of mechanical properties apart from tensile strength.
xi. Optimum stabiliser content was generally reported as 10% with higher cement contents resulting in higher UCS up to a certain point but due to the goal of creating a sustainable construction material, 10% was recommended as the max percentage required.
xii. Most common stabiliser used was cement.
xiii. The use of waste materials such as fly-ash required higher percentages of stabiliser by weight and the use of an activator in order to stabilise RE samples.
xiv. Chemically stabilised RE produced higher strength values than unstabilised RE.
xv. The addition of fibres can increase the various strength properties and seems to be the most significant method to improve the tensile strength of RE.
xvi. URE is capable to meeting minimum material property specifications depending on the soil type and chances of meeting these specifications are greatly increased by using chemical stabilisers and fibres.

From these observations, the following points of discussion arise. RE performs well in most areas, in terms of meeting minimum specifications from Table 2, apart from Young's Modulus. In fact, UCS values are mostly significantly higher than the minimum specifications and this leads to the question, are the specifications too low or are these UCS values higher than they need to be. If the latter is the case, is RE construction being over engineered? As mentioned in the observations, 10% cement was highlighted as the optimum content for stabilisation. Many of these recommendations were made as 10% cement resulted in the highest or close to the highest UCS values achieved under laboratory conditions. Stabiliser contents above 10%, while in many cases increased the UCS, may not be ideal as the increased carbon footprint of using higher amounts of cement would make the environmental benefits of earth construction to be less.

In relation to fibre reinforcement, it has been demonstrated in a number of the studies mentioned that their addition can improve shear and tensile strength up to a certain point. While such studies have focused on the mechanical behaviour of fibre reinforced earthen materials, few studies have been carried out looking at the effect of fibres on the interface between soil and the fibres [120, 121]. As the type of fibres used can vary, this relationship should be investigated when assessing novel fibrous materials for use in rammed earth.

Also shown is that the Young's modulus of RE in the majority of cases was less than that specified in Table 2. Therefore more research should be carried out to investigate ways to improve this material property or is the minimum specification in Table 2 unrealistic for RE.

5 Conclusions and recommendations

A systematic literature review was carried out in order to gain an understanding of the mechanical properties of rammed earth. Various strengthening measures such as chemical stabilisation and fibre reinforcement were investigated with UCS, bending, shear and tensile strength, as well as Young's modulus values being reported. This provided a clear picture of the different effects these strengthening techniques have on rammed earth. Unstabilised rammed earth can have adequate material properties for use in construction in seismically active zones, depending on the soil being used, but the use of chemical stabilisers and fibre reinforcement have been shown to improve the various mechanical properties discussed here. Enhancing the material properties is a way to allow for RE to built in seismically active zones, but the environmental benefits of using RE need to be taken into consideration. If too much cement and other additives are used to strengthen RE, could this affect the embodied carbon of rammed earth thus negatively affect its claim as a sustainable form of construction. With this in mind recommendations for further study include:

i. Further investigate if more sustainable alternatives to cement can be used as an effective chemical stabiliser, that can improve the mechanical properties of rammed earth and achieve similar strength improvements comparable to cement.
ii. Investigate alternative materials for fibre reinforcement, focusing on using waste materials, which can both improve rammed earths material properties and keep the embodied carbon of the material as low as possible.
iii. Standardise test methodologies for determining mechanical properties.
iv. Investigate whether minimum material property specifications for building with RE in seismically active zones are reflective of what is actually required. This could be achieved by developing a finite element model of an RE structure, using these minimum specifications, to determine the structures performance during seismic loading.

Acknowledgements The authors would like to thank the School of Transport & Civil Engineering at TU Dublin for facilitating this research.

Author contributions DT was responsible for conceptualization, methodology, investigation of sources, writing, producing charts and graphs and project administration CA: was responsible for reviewing and editing JPO was responsible for reviewing & editing All authors reviewed the manuscript.

Funding There is no external funding for this project. The School of Transport and Civil Engineering at TU Dublin has waived registration fees for David Thompson while completing his PhD of which this paper is part of.

Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

References

1. Monteiro PJM, Miller SA, Horvath A. Towards sustainable concrete. Nat Mater. 2017;16:698–9. https://doi.org/10.1038/nmat4930.
2. 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. https://doi.org/10.1016/j.jobe.2022.104666.
3. Perić A, Kraus I, Kaluđer J, Kraus L. Experimental campaigns on mechanical properties and seismic performance of unstabilized rammed earth—a literature review. Buildings. 2021. https://doi.org/10.3390/buildings11080367.
4. Avila F, Puertas E, Gallego R. Characterization of the mechanical and physical properties of unstabilized rammed earth: a review. Constr Build Mater. 2021. https://doi.org/10.1016/j.conbuildmat.2020.121435.
5. ASTM D-1633 Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinder. 2017; 17–20.
6. Maniatidis V, Walker P. A review of rammed earth construction for DTi partners in innovation project developing rammed earth for UK Housing; Dept. of Architecture & Civil Engineering, Natural Building, Technology Group: Bath, U.K., 2003.
7. El Nabouch R. Mechanical behavior of rammed earth walls under pushover tests. Proc Eng. 2016. https://doi.org/10.1016/j.proeng.2016.04.153.
8. Bueno AM, de PaulaXavier AA, Broday EE. Evaluating the connection between thermal comfort and productivity in buildings: a systematic literature review. Buildings. 2021. https://doi.org/10.3390/buildings11060244.
9. Araki H, Koseki J, Sato T. Tensile strength of compacted rammed earth materials. Soils Found. 2016;56:189–204. https://doi.org/10.1016/j.sandf.2016.02.003.

10. Beckett CTS, Augarde CE, Easton D, Easton T. Strength characterisation of soil-based construction materials. Geotechnique. 2018;68:400–9. https://doi.org/10.1680/jgeot.16.P.288.
11. Bui QB, Morel JC, Hans S, Walker P. Effect of moisture content on the mechanical characteristics of rammed earth. Constr Build Mater. 2014;54:163–9. https://doi.org/10.1016/j.conbuildmat.2013.12.067.
12. Bui TT, Bui QB, Limam A, Maximilien S. Failure of rammed earth walls: from observations to quantifications. Constr Build Mater. 2014;51:295–302. https://doi.org/10.1016/j.conbuildmat.2013.10.053.
13. Ciancio D, Jaquin P, Walker P. Advances on the assessment of soil suitability for rammed earth. Constr Build Mater. 2013;42:40–7. https://doi.org/10.1016/j.conbuildmat.2012.12.049.
14. Corbin A, Augarde C. Fracture energy of stabilised rammed earth. Procedia Mater Sci. 2014;3:1675–80. https://doi.org/10.1016/j.mspro.2014.06.270.
15. Fang S, Meng C, Zhang K, Hu W, Liu X. New insight into the craftsmanship of sucrose-modified rammed earth-lime materials. J Asian Arch Build Eng. 2022;21:1019–28. https://doi.org/10.1080/13467581.2021.1928505.
16. Hall M, Djerbib Y. Rammed earth sample production: context, recommendations and consistency. Constr Build Mater. 2004;18:281–6. https://doi.org/10.1016/j.conbuildmat.2003.11.001.
17. Hallal MM, Sadek S, Najjar SS. Evaluation of engineering characteristics of stabilized rammed-earth material sourced from natural fines-rich soil. J Mater Civ Eng. 2018. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002481.
18. Khadka B, Shakya M. Comparative compressive strength of stabilized and un-stabilized rammed earth. Mater Struct. 2016;49:3945–55. https://doi.org/10.1617/s11527-015-0765-5.
19. Kosarimovahhed M, Toufigh V. Sustainable usage of waste materials as stabilizer in rammed earth structures. J Clean Prod. 2020. https://doi.org/10.1016/j.jclepro.2020.123279.
20. Koutous A, Hilali E. Reinforcing rammed earth with plant fibers: a case study. Case Stud Construct Mater. 2021. https://doi.org/10.1016/j.cscm.2021.e00514.
21. Lin H, Zheng S, Lourenço SDN, Jaquin P. Characterization of coarse soils derived from igneous rocks for rammed earth. Eng Geol. 2017;228:137–45. https://doi.org/10.1016/j.enggeo.2017.08.003.
22. Liu X, Hu M, Ke S, Fu C, Guo X, Ye X. A novel rammed earthen material stabilized with steel slags. Constr Build Mater. 2018;189:1134–9. https://doi.org/10.1016/j.conbuildmat.2018.09.075.
23. Lombillo I, Villegas L, Fodde E, Thomas C. In situ mechanical investigation of rammed earth: calibration of minor destructive testing. Constr Build Mater. 2014;51:451–60. https://doi.org/10.1016/j.conbuildmat.2013.10.090.
24. Mabrouk Y, Benazzouk A, Lahmar A, Azrour M, Mocerino C, Lahmar A. Elaboration and characterization of lightweight rammed earth containing hemp particles. Mater Today Proc. 2022. https://doi.org/10.1016/j.matpr.2022.02.319.
25. Miccoli L, Müller U, Fontana P. Mechanical behaviour of earthen materials: a comparison between earth block masonry, rammed earth and cob. Constr Build Mater. 2014;61:327–39. https://doi.org/10.1016/j.conbuildmat.2014.03.009.
26. Narani SS, Zare P, Abbaspour M, Fahimifar A, Siddiqua S, Mir Mohammad Hosseini SM. Evaluation of fiber-reinforced and cement-stabilized rammed-earth composite under cyclic loading. Constr Build Mater. 2021;296: 123746. https://doi.org/10.1016/j.conbuildmat.2021.123746.
27. Porter H, Blake J, Dhami NK, Mukherjee A. Rammed earth blocks with improved multifunctional performance. Cem Concr Compos. 2018;92:36–46. https://doi.org/10.1016/j.cemconcomp.2018.04.013.
28. Raavi SSD, Tripura DD. Predicting and evaluating the engineering properties of unstabilized and cement stabilized fibre reinforced rammed earth blocks. Constr Build Mater. 2020. https://doi.org/10.1016/j.conbuildmat.2020.120845.
29. Raj S, Mohammad S, Das R, Saha S. Coconut fibre-reinforced cement-stabilized rammed earth blocks. World J Eng. 2017;14:208–16. https://doi.org/10.1108/WJE-10-2016-0101.
30. Ramezanpour M, Eslami A, Ronagh H. Seismic performance of stabilised/unstabilised rammed earth walls. Eng Struct. 2021. https://doi.org/10.1016/j.engstruct.2021.112982.
31. Sharma V, Vinayak HK, Marwaha BM. Enhancing compressive strength of soil using natural fibers. Constr Build Mater. 2015;93:943–9. https://doi.org/10.1016/j.conbuildmat.2015.05.065.
32. Toufigh V, Karamian MH, Ghasemalizadeh S. Study of Stress-strain and volume change behavior of fly ash-GBFS based geopolymer rammed earth. Bull Eng Geol Environ. 2021;80:6749–67. https://doi.org/10.1007/s10064-021-02292-5.
33. Tripura DD, Singh KD. Characteristic properties of cement-stabilized rammed earth blocks. J Mater Civ Eng. 2015. https://doi.org/10.1061/(asce)mt.1943-5533.0001170.
34. Xu L, Wong KK, Fabbri A, Champiré F, Branque D. Loading-unloading shear behavior of rammed earth upon varying clay content and relative humidity conditions. Soils Found. 2018;58:1001–15. https://doi.org/10.1016/j.sandf.2018.05.005.
35. Zare P, Sheikhi Narani S, Abbaspour M, Fahimifar A, Mir Mohammad Hosseini SM, Zare P. Experimental investigation of non-stabilized and cement-stabilized rammed earth reinforcement by waste tire textile fibers (WTTFs). Constr Build Mater. 2020. https://doi.org/10.1016/j.conbuildmat.2020.120432.
36. Patel A. Soil stabilization. In Geotechnical investigations and improvement of ground conditions. Elsevier, 2019; pp. 19–27.
37. Burroughs S. Soil property criteria for rammed earth stabilization. J Mater Civ Eng. 2008;20:264–73. https://doi.org/10.1061/(ASCE)0899-1561(2008)20:3(264).
38. Jayasinghe C, Kamaladasa N. Compressive strength characteristics of cement stabilized rammed earth walls. Constr Build Mater. 2007;21:1971–6. https://doi.org/10.1016/j.conbuildmat.2006.05.049.
39. Kariyawasam KKGKD, Jayasinghe C. Cement stabilized rammed earth as a sustainable construction material. Constr Build Mater. 2016;105:519–27. https://doi.org/10.1016/j.conbuildmat.2015.12.189.
40. Rogala W, Anysz H, Narloch P. Designing the composition of cement-stabilized rammed earth with the association analysis application. Materials. 2021. https://doi.org/10.3390/ma14061390.
41. Anysz H, Brzozowski Ł, Kretowicz W, Narloch P. Feature importance of stabilised rammed earth components affecting the compressive strength calculated with explainable artificial intelligence tools. Materials. 2020. https://doi.org/10.3390/ma13102317.

42. Narloch P, Piatkiewicz W, Pietruszka B. The effect of cement addition on water vapour resistance factor of rammed earth. Materials. 2021. https://doi.org/10.3390/ma14092249.
43. Narloch P, Woyciechowski P. Assessing cement stabilized rammed earth durability in a humid continental climate. Buildings. 2020. https://doi.org/10.3390/buildings10020026.
44. Rosicki Ł, Narloch P. Studies on the ageing of cement stabilized rammed earth material in different exposure conditions. Materials. 2022. https://doi.org/10.3390/ma15031090.
45. Consoli NC, Festugato L, Da Rocha CG, Cruz RC. key parameters for strength control of rammed sand-cement mixtures: influence of types of Portland cement. Constr Build Mater. 2013;49:591–7. https://doi.org/10.1016/j.conbuildmat.2013.08.062.
46. Ciancio D, Boulter M. Stabilised rammed earth: a case study in Western Australia. Proc Inst Civ Eng Eng Sustain. 2012;165:141–54. https://doi.org/10.1680/ensu.10.00003.
47. Walker PJ, Dobson S. Pullout tests on deformed and plain Rebars in cement-stabilized rammed earth. J Mater Civ Eng. 2001;13:291–7. https://doi.org/10.1061/(ASCE)0899-1561(2001)13:4(291).
48. Windstorm B, Schmidt A. A report of contemporary rammed earth construction and research in North America. Sustainability (Switzerland). 2013;5:400–16. https://doi.org/10.3390/su5020400.
49. Ciancio D, Beckett CTS, Carraro JAH. Optimum lime content identification for lime-stabilised rammed earth. Constr Build Mater. 2014;53:59–65. https://doi.org/10.1016/j.conbuildmat.2013.11.077.
50. Bui QB. Assessing the rebound hammer test for rammed earth material. Sustainability (Switzerland). 2017. https://doi.org/10.3390/su9101904.
51. Ciancio D, Robinson S. Use of the strut-and-tie model in the analysis of reinforced cement-stabilized rammed earth lintels. J Mater Civ Eng. 2011;23:587–96. https://doi.org/10.1061/(asce)mt.1943-5533.0000215.
52. Jayasinghe C, Fonseka WMCDJ, Abeygunawardhene YM. Load bearing properties of composite masonry constructed with recycled building demolition waste and cement stabilized rammed earth. Constr Build Mater. 2016;102:471–7. https://doi.org/10.1016/j.conbuildmat.2015.10.136.
53. Meek AH, Elchalakani M, Beckett CTS, Grant T. Alternative stabilised rammed earth materials incorporating recycled waste and industrial by-products: life cycle assessment. Constr Build Mater. 2021. https://doi.org/10.1016/j.conbuildmat.2020.120997.
54. Otcovská TP, Mužíková B, Padevět P. Mechanical properties of rammed earth with respect to clay mixture composition. Acta Polytech. 2019;59:372–83. https://doi.org/10.14311/AP.2019.59.0372.
55. Shrestha KC, Aoki T, Miyamoto M, Wangmo P. pema in-plane shear resistance between the rammed earth blocks with simple interventions: experimentation and finite element study. Buildings. 2020. https://doi.org/10.3390/buildings10030057.
56. Strazzeri V, Karrech A, Elchalakani M. Micromechanics modelling of cement stabilised rammed earth. Mech Mater. 2020. https://doi.org/10.1016/j.mechmat.2020.103540.
57. Raju L, Venkatarama Reddy BV. Influence of layer thickness and plasticizers on the characteristics of cement-stabilized rammed earth. J Mater Civ Eng. 2018. https://doi.org/10.1061/(asce)mt.1943-5533.0002539.
58. Narloch P, Woyciechowski P, Kotowski J, Gawriuczenkow I, Wójcik E. The effect of soil mineral composition on the compressive strength of cement stabilized rammed earth. Materials. 2020. https://doi.org/10.3390/ma13020324.
59. Lepakshi R, Venkatarama Reddy BV. Shear strength parameters and Mohr-Coulomb failure envelopes for cement stabilised rammed earth. Constr Build Mater. 2020. https://doi.org/10.1016/j.conbuildmat.2020.118708.
60. Pavan GS, Ullas SN, NanjundaRao KS. Interfacial behavior of cement stabilized rammed earth: experimental and numerical study. Constr Build Mater. 2020. https://doi.org/10.1016/j.conbuildmat.2020.119327.
61. Pavan GS, Ullas SN, Nanjunda Rao KS. Shear behavior of cement stabilized rammed earth assemblages. J Build Eng. 2020. https://doi.org/10.1016/j.jobe.2019.100966.
62. Narloch PL, Lidner M, Kunicka E, Bielecki M. Flexural tensile strength of construction elements made out of cement stabilized rammed earth. Proc Eng. 2015;111:589–95.
63. Anysz H, Narloch P. Designing the composition of cement stabilized rammed earth using artificial neural networks. Materials. 2019. https://doi.org/10.3390/ma12091396.
64. Vilane BRT. Assessment of stabilisation of adobes by confined compression tests. Biosyst Eng. 2010;106:551–8. https://doi.org/10.1016/j.biosystemseng.2010.06.008.
65. 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. https://doi.org/10.1016/j.conbuildmat.2018.09.207.
66. Beckett C, Ciancio D. Effect of compaction water content on the strength of cement-stabilized rammed earth materials. Can Geotech J. 2014;51:583–90. https://doi.org/10.1139/cgj-2013-0339.
67. Honne Basanna N, Hirebelaguly Shivaprakash S, Bhimahalli A, Parameshwarappa PK, Gaudin J. Role of stabilizers and gradation of soil in rammed earth construction. J Mater Civ Eng. 2020. https://doi.org/10.1061/(asce)mt.1943-5533.0003112.
68. Ajabi Naeini A, Siddiqua S, Cherian C. A novel stabilized rammed earth using pulp mill fly ash as alternative low carbon cementing material. Constr Build Mater. 2021;300: 124003. https://doi.org/10.1016/j.conbuildmat.2021.124003.
69. Elahi TE, Shahriar AR, Islam MS, Mehzabin F, Mumtaz N. Suitability of fly ash and cement for fabrication of compressed stabilized earth blocks. Constr Build Mater. 2020;263: 120935. https://doi.org/10.1016/j.conbuildmat.2020.120935.
70. Elahi TE, Shahriar AR, Islam MS. Engineering characteristics of compressed earth blocks stabilized with cement and fly ash. Constr Build Mater. 2021;277: 122367. https://doi.org/10.1016/j.conbuildmat.2021.122367.
71. Islam MS, Elahi TE, Shahriar AR, Mumtaz N. Effectiveness of fly ash and cement for compressed stabilized earth block construction. Constr Build Mater. 2020;255: 119392. https://doi.org/10.1016/j.conbuildmat.2020.119392.
72. Arrigoni A, Beckett CTS, Ciancio D, Pelosato R, Dotelli G, Grillet AC. Rammed earth incorporating recycled concrete aggregate: a sustainable, resistant and breathable construction solution. Resour Conserv Recycl. 2018;137:11–20. https://doi.org/10.1016/j.resconrec.2018.05.025.

73. 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. https://doi.org/10.1016/j.jclepro.2013.11.041.
74. Milani APdS, Labaki LC. Physical, mechanical, and thermal performance of cement-stabilized rammed earth-rice husk ash walls. J Mater Civ Eng. 2012;24:775–82. https://doi.org/10.1061/(asce)mt.1943-5533.0000439.
75. Gu K, Chen B. Loess stabilization using cement, waste phosphogypsum, fly ash and quicklime for self-compacting rammed earth construction. Constr Build Mater. 2020. https://doi.org/10.1016/j.conbuildmat.2019.117195.
76. Raj SS, Sharma AK, Anand KB. Performance appraisal of coal ash stabilized rammed earth. J Build Eng. 2018;18:51–7. https://doi.org/10.1016/j.jobe.2018.03.001.
77. Siddiqua S, Barreto PNM. Chemical stabilization of rammed earth using calcium carbide residue and fly ash. Constr Build Mater. 2018;169:364–71. https://doi.org/10.1016/j.conbuildmat.2018.02.209.
78. Cristelo N, Glendinning S, Miranda T, Oliveira D, Silva R. soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction. Constr Build Mater. 2012;36:727–35. https://doi.org/10.1016/j.conbuildmat.2012.06.037.
79. Khan A, Gupta R, Garg M. Determining material characteristics of "rammed earth" using non-destructive test methods for structural design. Structures. 2019;20:399–410. https://doi.org/10.1016/j.istruc.2019.05.003.
80. Ma C, Xie Y, Long G. A calculation model for compressive strength of cleaner earth-based construction with a high-efficiency stabilizer and fly ash. J Clean Prod. 2018;183:292–303. https://doi.org/10.1016/j.jclepro.2018.02.153.
81. Narayanaswamy AH, Walker P, Venkatarama Reddy BV, Heath A, Maskell D. Mechanical and thermal properties, and comparative lifecycle impacts, of stabilised earth building products. Constr Build Mater. 2020. https://doi.org/10.1016/j.conbuildmat.2020.118096.
82. Silva RA, Oliveira DV, Miranda T, Cristelo N, Escobar MC, Soares E. Rammed earth construction with granitic residual soils: the case study of Northern Portugal. Constr Build Mater. 2013;47:181–91. https://doi.org/10.1016/j.conbuildmat.2013.05.047.
83. Türkmen İ, Ekinci E, Kantarcı F, Sarıcı T. The mechanical and physical properties of unfired earth bricks stabilized with gypsum and elaziğ ferrochrome slag. Int J Sustain Built Environ. 2017;6:565–73. https://doi.org/10.1016/j.ijsbe.2017.12.003.
84. Cuccurullo A, Gallipoli D, Bruno AW, Augarde C, Hughes P, La Borderie C. Advances in the ENZYMATIC STABILISATION OF SOIls. In Proceedings of the 17th European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2019 - Proceedings; International Society for Soil Mechanics and Geotechnical Engineering, 2019; Vol. 2019-September.
85. Cuccurullo A, Gallipoli D, Bruno AW, Augarde C, Hughes P, La Borderie C. Earth stabilisation via carbonate precipitation by plant-derived urease for building applications. Geomech Energy Environ. 2022. https://doi.org/10.1016/j.gete.2020.100230.
86. Geotechnical Research for Land Protection and Development; Calvetti F, Cotecchia F, Galli A, Jommi C, editors. Lecture Notes in Civil Engineering; Springer International Publishing: Cham, 2020; Vol. 40; ISBN 978-3-030-21358-9.
87. Laborel-Préneron A, Aubert JE, Magniont C, Tribout C, Bertron A. Plant aggregates and fibers in earth construction materials: a review. Constr Build Mater. 2016;111:719–34.
88. Hejazi SM, Sheikhzadeh M, Abtahi SM, Zadhoush A. A simple review of soil reinforcement by using natural and synthetic fibers. Constr Build Mater. 2012;30:100–16.
89. Al-Subari L, Ekinci A, Aydın E. The utilization of waste rubber tire powder to improve the mechanical properties of cement-clay composites. Constr Build Mater. 2021. https://doi.org/10.1016/j.conbuildmat.2021.124306.
90. Sabbà MF, Tesoro M, Falcicchio C, Foti D. Rammed earth with straw fibers and earth mortar: mix design and mechanical characteristics determination. Fibers. 2021. https://doi.org/10.3390/fib9050030.
91. Sri Bhanupratap Rathod R, Venkatarama Reddy BV, Rathod RSB, Reddy BVV. Strength and stress-strain characteristics of fibre reinforced cement stabilised rammed earth. Mater Struct/Materiaux et Constructions. 2021. https://doi.org/10.1617/s11527-021-01640-x.
92. Tran KQ, Satomi T, Takahashi H. Improvement of mechanical behavior of cemented soil reinforced with waste cornsilk fibers. Constr Build Mater. 2018;178:204–10. https://doi.org/10.1016/j.conbuildmat.2018.05.104.
93. Mellaikhafi A, Ouakarrouch M, Benallel A, Tilioua A, Ettakni M, Babaoui A, Garoum M, Alaoui Hamdi MA. Characterization and thermal performance assessment of earthen adobes and walls additive with different date palm fibers. Case Stud Constr Mater. 2021;15: e00693. https://doi.org/10.1016/j.cscm.2021.e00693.
94. Olacia E, Pisello AL, Chiodo V, Maisano S, Frazzica A, Cabeza LF. Sustainable adobe bricks with seagrass fibres. Mechanical and thermal properties characterization. Constr Build Mater. 2020;239: 117669. https://doi.org/10.1016/j.conbuildmat.2019.117669.
95. Babé C, Kidmo DK, Tom A, Mvondo RRN, Kola B, Djongyang N. Effect of neem (Azadirachta Indica) fibers on mechanical, thermal and durability properties of adobe bricks. Energy Rep. 2021;7:686–98. https://doi.org/10.1016/j.egyr.2021.07.085.
96. Eslami A, Mohammadi H, Mirabi Banadaki H. Palm fiber as a natural reinforcement for improving the properties of traditional adobe bricks. Constr Build Mater. 2022;325: 126808. https://doi.org/10.1016/j.conbuildmat.2022.126808.
97. Danso H, Martinson DB, Ali M, Williams J. Effect of fibre aspect ratio on mechanical properties of soil building blocks. Constr Build Mater. 2015;83:314–9. https://doi.org/10.1016/j.conbuildmat.2015.03.039.
98. Kumar N, Barbato M. Effects of sugarcane bagasse fibers on the properties of compressed and stabilized earth blocks. Constr Build Mater. 2022;315: 125552. https://doi.org/10.1016/j.conbuildmat.2021.125552.
99. Danso H, Martinson DB, Ali M, Williams JB. Physical, mechanical and durability properties of soil building blocks reinforced with natural fibres. Constr Build Mater. 2015;101:797–809. https://doi.org/10.1016/j.conbuildmat.2015.10.069.
100. Mostafa M, Uddin N. Experimental analysis of compressed earth block (CEB) with banana fibers resisting flexural and compression forces. Case Stud Constr Mater. 2016;5:53–63. https://doi.org/10.1016/j.cscm.2016.07.001.
101. Cottrell JA, Ali M, Tatari A, Martinson DB. Effects of fibre moisture content on the mechanical properties of jute reinforced compressed earth composites. Constr Build Mater. 2023;373: 130848. https://doi.org/10.1016/j.conbuildmat.2023.130848.
102. Stanislas TT, Tendo JF, Teixeira RS, Ojo EB, Komadja GC, Kadivar M, Junior HS. Effect of cellulose pulp fibres on the physical, mechanical, and thermal performance of extruded earth-based materials. J Build Eng. 2021;39: 102259. https://doi.org/10.1016/j.jobe.2021.102259.
103. Pekrioglu Balkis A. The effects of waste marble dust and polypropylene fiber contents on mechanical properties of gypsum stabilized earthen. Constr Build Mater. 2017;134:556–62. https://doi.org/10.1016/j.conbuildmat.2016.12.172.

104. Akhzeroun A, Semcha A, Bezazi A, Boumediri H, Reis PNB, Scarpa F. Development and characterization of a new sustainable composite reinforced with date palm stems for rehabilitation and reconstruction of earthen built heritage. Compos Struct. 2023;316: 117015. https://doi.org/10.1016/j.compstruct.2023.117015.
105. Praveen GV, Kurre P. Influence of coir fiber reinforcement on shear strength parameters of cement modified marginal soil mixed with fly ash. Mater Today Proc. 2021;39:504–7. https://doi.org/10.1016/j.matpr.2020.08.238.
106. Wang J, Hughes PN, Augarde CE. Towards a predictive model of the shear strength behaviour of fibre reinforced clay. Eur J Environ Civ Eng. 2023. https://doi.org/10.1080/19648189.2023.2214596.
107. Wang J, Hughes PN, Augarde CE. Effects of fibre additions on the tensile strength and crack behaviour of unsaturated clay. Proc Inst Civ Eng Ground Improv. 2023;176:108–20. https://doi.org/10.1680/jgrim.21.00006.
108. Li J, Tang C, Wang D, Pei X, Shi B. Effect of discrete fibre reinforcement on soil tensile strength. J Rock Mech Geotech Eng. 2014;6:133–7. https://doi.org/10.1016/j.jrmge.2014.01.003.
109. Aymerich F, Fenu L, Meloni P. Effect of reinforcing wool fibres on fracture and energy absorption properties of an earthen material. Constr Build Mater. 2012;27:66–72. https://doi.org/10.1016/j.conbuildmat.2011.08.008.
110. Wang JY, Hughes PN, Augarde CE. CBR strength of london clay reinforced with polypropylene fibre. In Proceedings of the 17th European Conference on Soil Mechanics and Geotechnical Engineering, ECSMGE 2019—Proceedings; International Society for Soil Mechanics and Geotechnical Engineering, 2019; Vol. 2019-September.
111. Australia Standards, Walker P. Australian Earth Building Handbook—HB 195; Standards Australia: Sydney, Austraila, 2002; ISBN 9781849770958.
112. Standards New Zealand NZS 4297—Engineering Design of Earthen Buildings 1998, NZS 4297, 63.
113. Construction Industries Division of the Regulation and Licensing Department The New Mexico Earthen Building Materials Code. Title 14, Chapter 7, Part 4 2016.
114. Luo Y, Zhou P, Ma H, Ni P, Ding N, Xu Y. Energy dissipation of rammed earth-timber joints under cyclic loading. Soil Dyn Earthq Eng. 2021. https://doi.org/10.1016/j.soildyn.2021.106728.
115. Chauhan P, El Hajjar A, Prime N, Plé O. Unsaturated behavior of rammed earth: experimentation towards numerical modelling. Constr Build Mater. 2019. https://doi.org/10.1016/j.conbuildmat.2019.08.027.
116. Miccoli L, Drougkas A, Müller U. In-plane behaviour of rammed earth under cyclic loading: experimental testing and finite element modelling. Eng Struct. 2016;125:144–52. https://doi.org/10.1016/j.engstruct.2016.07.010.
117. Silva RA, Oliveira DV, Schueremans L, Lourenço PB, Miranda T. Modelling the structural behaviour of rammed earth components. Civil-Comp Proc. 2014. https://doi.org/10.4203/ccp.106.112.
118. Silva RA, Oliveira DV, Miccoli L, Schueremans L. Modelling of rammed earth under shear loading. SAHC2014–9th International Conference on Structural Analysis of Historicak Constructions. 2014, 14–17.
119. Corbin A, Augarde C. Investigation into the shear behaviour of rammed earth using shear box tests. First international conference on bio-based building materials. 2015; 33: 93–98.
120. Readle D, Coghlan S, Smith JC, Corbin A, Augarde CE. Fibre reinforcement in earthen construction materials. Proc Inst Civ Eng Constr Mater. 2016;169:252–60. https://doi.org/10.1680/jcoma.15.00039.
121. Vincenzini A, Augarde CE, Gioffrè M. Experimental characterization of natural fibre-soil interaction: lessons for earthen construction. Mater Struct/Mater Constr. 2021. https://doi.org/10.1617/s11527-021-01703-z.