

A descriptive view of rammed earth performance: bibliometric analysis and systematic literature review

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Abstract:

Rammed earth is a sustainable material with several features that warrant being studied and analysed for safe use as a green building for low-rise buildings due to its minimal CO₂ emissions. The initial section of this paper used bibliometric analysis to review various studies conducted on rammed earth from 2010 to 2024, comprising 960 publications. The subsequent section presents a systematic literature review of 52 publications, focusing on the mechanical properties of rammed earth, such as compressive strength, tensile strength, shear strength, and shear parameters (friction angle and cohesion), as well as thermal performance. The analysis of the outcomes of the previous studies showed that the compressive strength of unstabilised rammed earth ranges from 1 to 2.75 MPa, while stabilised rammed earth exhibits a range of 1.2 to 9.40 MPa, which is adequate for single-story and double-story buildings. The tensile strengths are reported to be between 0.16 and 0.38 MPa for unstabilized rammed earth, and the incorporation of fibres and chemical stabilisers increases them to the range of 0.73 to 1.16 MPa. Furthermore, the seismic behaviour of rammed earth is affected by its shear strength, which is only a small fraction of compressive strength, ranging from 7% to 10%, and is dependent on cohesion and friction angle. This study also developed an expression for predicting the tensile strength of rammed earth based on the percentage of fibres and chemical stabilisers used.

Keywords:

rammed earth, green buildings, mechanical properties, tensile strength, shear strength, thermal performance

1. Introduction

Earth construction is a sustainable technology that combines traditionality and modernity because it has been used by humans since ancient times, as attested to by historical monuments found in cities around the world. Recent developments in the construction industry, including the trend toward green buildings and pollution phenomena, have shown that the construction sector accounted for 37% of the global energy-related CO₂ emissions in 2020, including the operational and construction phases [1]. This makes it essential to investigate low-emission alternatives. Rammed earth, which uses compacted moist soil (clay, silt, sand, and a small percentage of gravel) in temporary formwork, is recognised for its environmental benefits, low carbon footprint and low embodied energy compared to traditional materials [2,3]. Therefore, it is important to assess its mechanical, seismic, and thermal properties to comprehensively evaluate its strengths and limitations as an alternative to concrete. Shear strength is the weakest strength of earthen materials; hence, it is necessary to conduct research in this field to enhance its resistance, especially because the susceptibility of these buildings to seismic activity has resulted in considerable loss and destruction [4]. Moreover, rammed earth buildings are often 10–50% cheaper than reinforced concrete houses, stone walls, and fired bricks, particularly when soil is available locally [5–8]. For instance, in India, a 42 m² house costs 35% less than another reinforced concrete house [7].

Therefore, experimental tests, such as diagonal compression, horizontal tests, and shaking table tests, provide indirect and direct techniques for studying the behaviour of rammed earth RE reinforced by innovative technologies. Furthermore, advanced numerical modelling approaches, such as finite element and discrete element modelling, have been applied to simulate and analyse the seismic behaviour of rammed earth walls, offering useful insights into their performance under various earthquake intensities [9,10].

Hence, studying the mechanical properties of earthen materials in general, and rammed earth in particular, is necessary, especially in the Middle East and North Africa (MENA). The latter is one of the richest regions in terms of historical monuments, thanks to its strategic location as a bridge between Europe and Africa. Several monuments and buildings in rural areas were built with earthen materials, particularly rammed earth, which is widespread around the Mediterranean, China, and the Himalayas [11–14] and also used as modern rammed earth buildings in Australia and North America [15]. Chronologically, the interest in rammed earth walls initially stemmed from a restoration perspective, given that most archaeological sites consist of earthen constructions, and heritage organisations, such as UNESCO and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), were among the first to fund studies on this type of building. In 1979, the Centre international de la construction en terre (Craterre) was established by the École Nationale Supérieure d'Architecture de Grenoble, and it was the first organisation to

focus solely on the exploration and development of techniques related to earthen construction. Many countries famous for using rammed earth are located in a geographical areas with a high risk of earthquakes, and several earthquakes have occurred over the last century (Agadir 1960; Chlef 1980, Al-Hoceima 2004; Buthan 2009, Nepal 2015, Al-Haouz 2023) [16–19]. The interest in the mechanical efficiency of this material, especially seismic performance and shear strength, can be a good solution for the retrofitting and restoration of monuments, as well as encouraging ecological construction with low embodied energy and low heating, ventilation, and cooling (HVAC).

This study focuses on rammed earth as the main earthen building technology because approximately 37% of research production is in RE, followed by adobe at 17% [20]. Many studies have investigated rammed earth; however, many of these papers have analysed rammed earth as a type of earthen building [4,20–26], and only a few papers have focused on rammed earth [4,22–24]. Two of these papers, [4,23] focused on unstabilized rammed earth and its mechanical and seismic properties, whereas [24] focused on a systematic literature review without diving into mechanical and thermal properties and a limited description of the tests, particularly compression and diagonal compression tests. The main goal of this study is to map the research landscape in Scopus (bibliometric analysis) by visualising key topics and both local and year distribution, and diving into the literature related to mechanical and thermal properties to explore and understand the strengths and weaknesses of rammed earth. Moreover, this study was not limited to simply collecting prior studies and tabulating their data; it also developed a polynomial to predict tensile strength based on the literature.

This study used two methods to analyse previous contributions to the study of the use of rammed earth in construction. Thus, the steps were taken in order to achieve the study’s aim:

- i. Collation of a list of relevant articles on rammed earth published in journals in the last 15 years, and determine the distribution of the publications by author(s), year and location, and keywords
- ii. Collation information on the following from selected relevant literature;
 - a. Compressive strength (f_c) of rammed earth and the effect of stabilisers, and shapes on value
 - b. Tensile strength (f_t) and how stabilisers improved the value
 - c. Shear strength of rammed earth and other shear parameters (cohesion, friction angle)
 - d. How reinforced solutions enhance the seismic performance of rammed earth

2. Methodology

2.1. Bibliometric analysis approach

The PRISMA framework [27] was used for bibliometric analysis. This review examined rammed earth, identified the leading countries and academic institutions, highlighted the top journals, recognised the most prolific authors, and analysed the most prevalent trends and keywords in rammed earth research.

In addition to the PRISMA framework, researchers used VosViewer for data visualisation, mapping, and analysis of complicated networks that comprised RE research in this study. VosViewer is a software program specifically designed to facilitate the management of bibliometric networks. This network can include authors, institutions, journals, and publications. The key elements in these networks include co-occurrence, co-citation, co-authors, citations, and bibliometric coupling links. Moreover, this tool can be used to study large databases extracted from the Web of Science, Scopus, Lens, Dimensions, and PubMed.

- Database selection

This review took place on February 22, 2025, Scopus database was selected as the main database for the bibliometric analysis section because Scopus is a prestigious database for a successful scientific analysis of published papers.

- Search string

To ensure the clarity of publications collected, the researchers used specific keywords, to code the search strings on VosViewer – “rammed earth” was searched using the code TITLE-ABS-KEY ("rammed" AND "earth"). Other criteria for the literature search on Scopus and the code used on VosViewer are as follows;

- i. Publications between 2010 and 2024 – “AND PUBYEAR >2009 AND PUBYEAR < 2025”
- ii. Subject area – Engineering, Materials Science, Environmental Science, Computer Science, and Energy – “AND LIMIT-TO (SUBJAREA , “ENG”) OR LIMIT-TO (SUBJAREA , “MATE”) OR LIMIT-TO (SUBJAREA , “ENER”) OR LIMIT-TO (SUBJAREA , “ENVI”) OR LIMIT-TO (SUBJAREA , “COMP”)”
- iii. Types of publications – articles and conference papers; “AND (LIMIT-TO (DOCTYPE , “ar”) OR LIMIT-TO (DOCTYPE , “cp”))”
- iv. Publication language – English; “AND (LIMIT-TO (LANGUAGE , “English”))”

Table 1, shows the number of publications included or excluded based on the criteria for inclusion or exclusion of any of the publications found during the literature search.

- Inclusion and reporting

Based on the PRISMA framework [27], the outcome of the bibliometric analysis is depicted in Fig. 1. This enabled the researchers to address the research questions in the next section.

Table 1. Total number of publications included or excluded based on inclusion or exclusion criteria

Inclusion criteria	TP included	Exclusion criteria	TP excluded
Rammed earth	1565	-	-
2010-2024	1455	All publications before 2010 and those after 2024.	110
Engineering, Materials science, Environmental science, Computer science and Energy	1284	Any other subject area	281
Articles and conference papers	1046	Book chapter, review, conference review, note, erratum, book, short survey.	519
English language	960	Any other language.	605

TP= Total Publications.

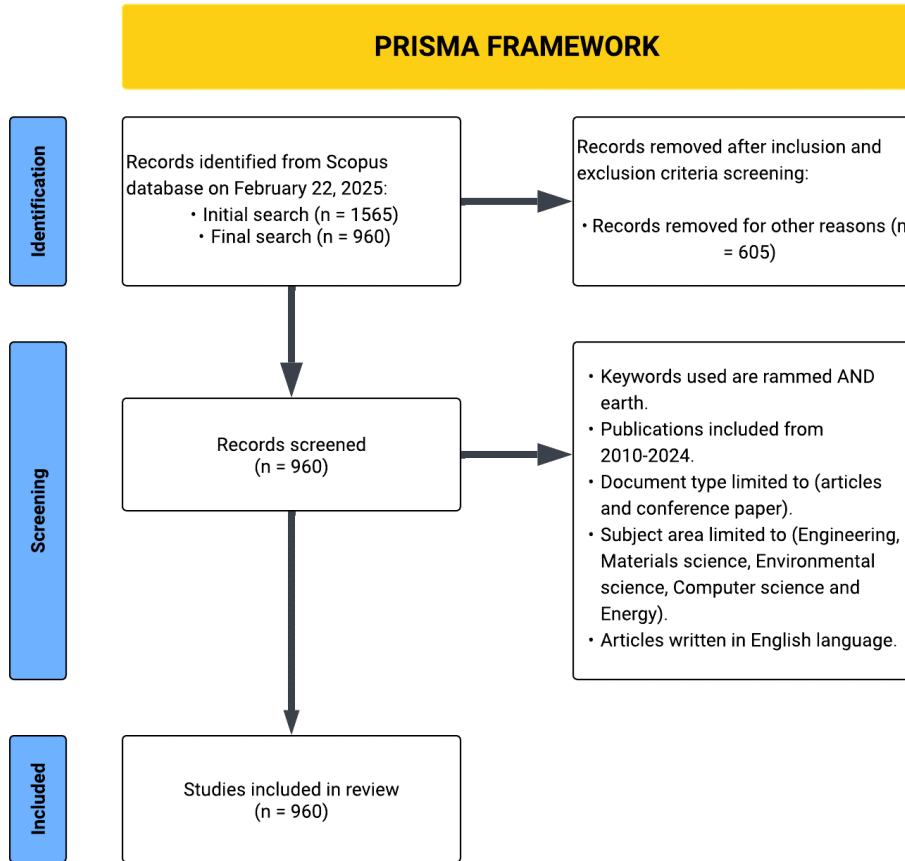


Fig. 1. Prisma framework for bibliometric analysis review

2.2. Systematic analysis review

In this systematic literature review (SLR), the authors focused on the relevant publications from 2010 to 2024 that touch on critical topics related to the mechanical strength of rammed earth, such as the compressive strength, tensile strength, shear strength, cohesion, friction angle, seismic performance, and thermal performance (see Fig. 2), and the influence of stabilizers and fibers on these parameters based on experimental studies. This study also covered the articles addressing the relationship between mechanical strengths, with the majority of the selected publications analysing at least two mechanical parameters. Authors excluded review publications, and those didn't investigate the mechanical strengths or thermal performance of rammed earth directly. The study also provides a synthesis based on these publications, establishing connections among them to guide a systematic review of the subject. It also aims to compile information from previous works, offer a novel perspective, and compare various data collected in these studies.

This study selected 37 articles and 5 conference papers, and both are indexed in Scopus, along with two theses and 9 books, including 4 national regulations (see Fig. 2). The selected national regulations for earthen building include the Australian Handbook, the New Zealand Standard, the national Colombian regulation, and the Moroccan regulation of earthen constructions. These regulations have been chosen to examine the methodologies employed in calculating mechanical strength and to identify the specific mechanical strengths addressed by these national standards.

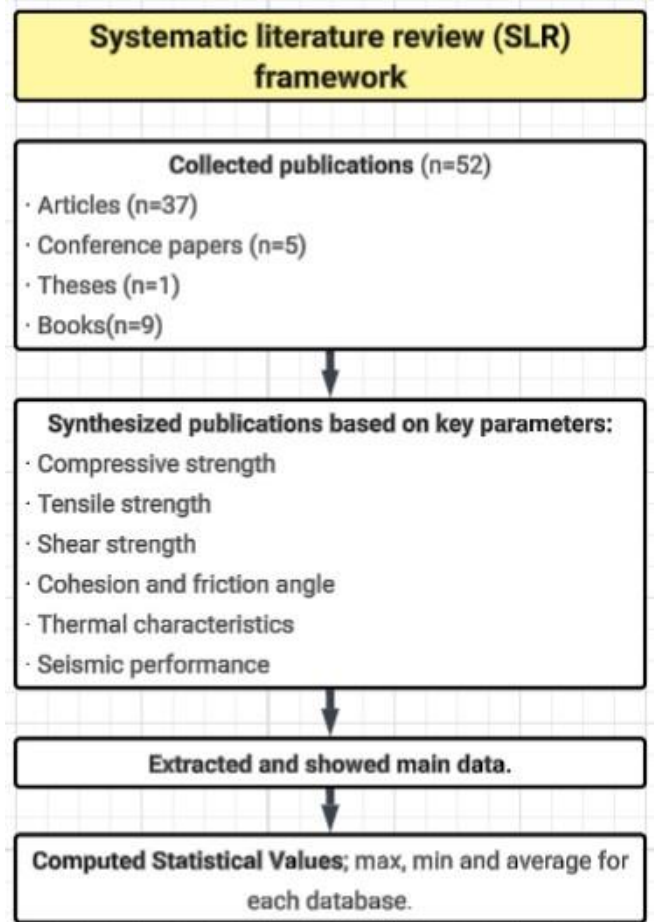


Fig. 2. Systematic literature review (SLR) framework

3. Results

3.1. Bibliometric analysis

3.1.1. Distribution of publications on rammed earth from 2010 to 2024

Figure 3 shows a significant increase in the number of publications that focused on rammed earth since 2015, when the average number of publications in this period was 78, while the overall average during the period from 2010 to 2024 was 64 publications. The years 2018 and 2024 recorded the highest number of publications on this subject, with 95 publications, while the total publications (TP) were only 8 in 2010. This high increase proves the interest in this subject as a means of sustainable construction with low energy consumption.

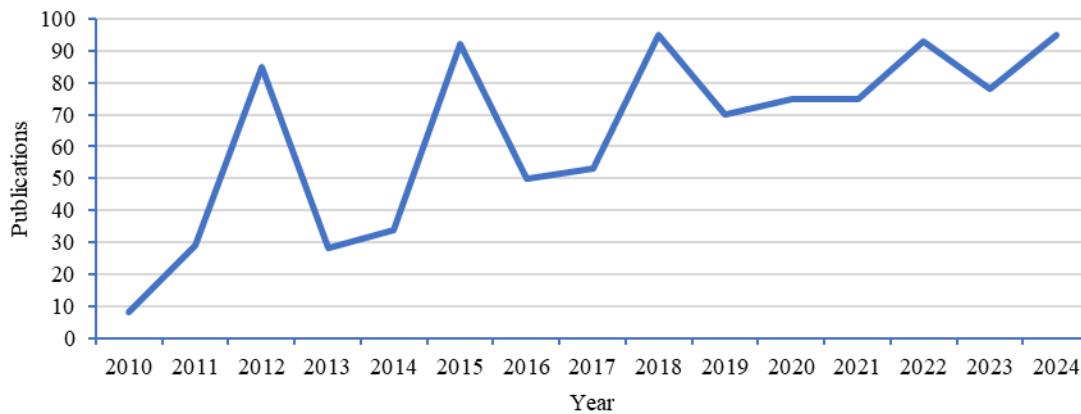


Fig. 3. The distribution of rammed earth publications in the period between 2010 and 2024

3.1.2. The top journals that focus on rammed earth

Table 2 shows that the Construction and Building Materials Journal published more articles on rammed earth than other journals, with total publications of 15336; 110 of these are related to rammed earth (0.72% of total), and citations of 211152, followed by Advanced Materials Research Journal with a total publication of 128196; 31 of them are related to rammed earth (0.02% of total) in the period between 2010 and 2014 because it has been excluded from Scopus since 2014. In addition, the third-ranked journal with a high number of publications rammed earth is the International Journal of Architectural Heritage, with 411 publications; 29 of which are related to rammed earth (7.06% of the total) and 2977 citations. Moreover, Elsevier and the Multidisciplinary Digital Publishing Institute (MDPI) are significant publishers in this subject area.

Table 2. The most relevant journals in rammed earth research

Journal	TP ^[1]	TC ^[1]	Citation score ^[1]	Most cited article	Times cited	Publisher
Construction and Building Materials	15336	211152	13.8	Differing perspectives on the use of high-content SBS polymer-modified bitumen	79	Elsevier
Advanced Materials Research ^[2]	128196	-	-	Modelling and simulating textile structures using TexGen	201	Trans Tech Publications
International Journal of Architectural Heritage	411	2977	7.2	Shaping Digital Twin Concept for Built Cultural Heritage Conservation: A Systematic Literature Review	23	Taylor & Francis
Sustainability (Switzerland)	55991	381357	6.8	Recent Advances in the Remediation of Textile-Dye-Containing Wastewater: Prioritising Human Health and Sustainable Wastewater Treatment	81	Multidisciplinary Digital Publishing Institute (MDPI)
Engineering Structures	6077	61732	10.2	Ultra-High-Strength Engineered Cementitious Composites (UHS-ECC) panel reinforced with FRP bar/grid: Development and flexural performance	80	Elsevier
Journal of Materials in Civil Engineering	2116	12304	5.8	Unified Characterisation of Rubber Asphalt Mixture Strength under Different Stress Loading Paths	26	American Society of Civil Engineers
Materials	30074	173808	5.8	Biomedical Applications of Titanium Alloys: A Comprehensive Review	57	Multidisciplinary Digital Publishing Institute (MDPI)
Materials and structures Materiaux et constructions	754	4794	6.4	Influence of electrophoretic deposition of micro- or nanosized silica particles on the microstructure of carbon fibres and their bond behaviour with cementitious matrices	16	Springer Nature
Journal of Building Engineering	7051	70200	10.0	Prediction of concrete and FRC properties at high temperature using machine and deep learning: A review of recent advances and future perspectives	77	Elsevier
Buildings	6258	21439	3.4	Probabilistic Analysis of Strength in Retrofitted X-Joints under Tensile Loading and Fire Conditions	35	Multidisciplinary Digital Publishing Institute (MDPI)

TP= Total Publications, TC= Total Citations. ^[1] = calculated on 05 May, 2024. ^[2] = excluded from Scopus since 2014 and database is only for years 2010-2014.

3.1.3. Geographical distribution of rammed earth publications in 2010-2024

Figure 4 shows the distribution of contributing countries in rammed earth between 2010 and 2024. China is the biggest contributor of rammed earth with 160 publications, while the second and third contributors are Spain and France with 156 and 97 publications, respectively. The total number of countries that contributed to the publications was 70 out of the 195 countries in the world – this represents an average of 17.1 publications. This result informs that many countries are yet to start research into the use of rammed earth for construction as statistics shows that only about 35% of the 195 countries of the world have contributed to this subject.

Figure 5 depicts the network co-authorship of the countries (72 countries) with the highest publications on rammed earth

research, with a maximum number of 25 countries per publication, as well as a limit to countries with no less than 5 publications in order to show significant links and collaboration between countries (33 countries) on the map. The size of the nodes corresponds to the number of publications from each of these 33 countries.

This network visualisation shows that countries are divided into 6 clusters, which means the strength of collaboration between countries in the same group. Furthermore, with linkages between 13 nations, France has the strongest overall link strength (64), followed by the UK (46), which has links between 11 countries. The fact that there are only 13 nations linked to China and 26 total link strengths (although China has the most publications on rammed earth), indicates that the majority of Chinese articles are the result of national collaboration among co-authors.

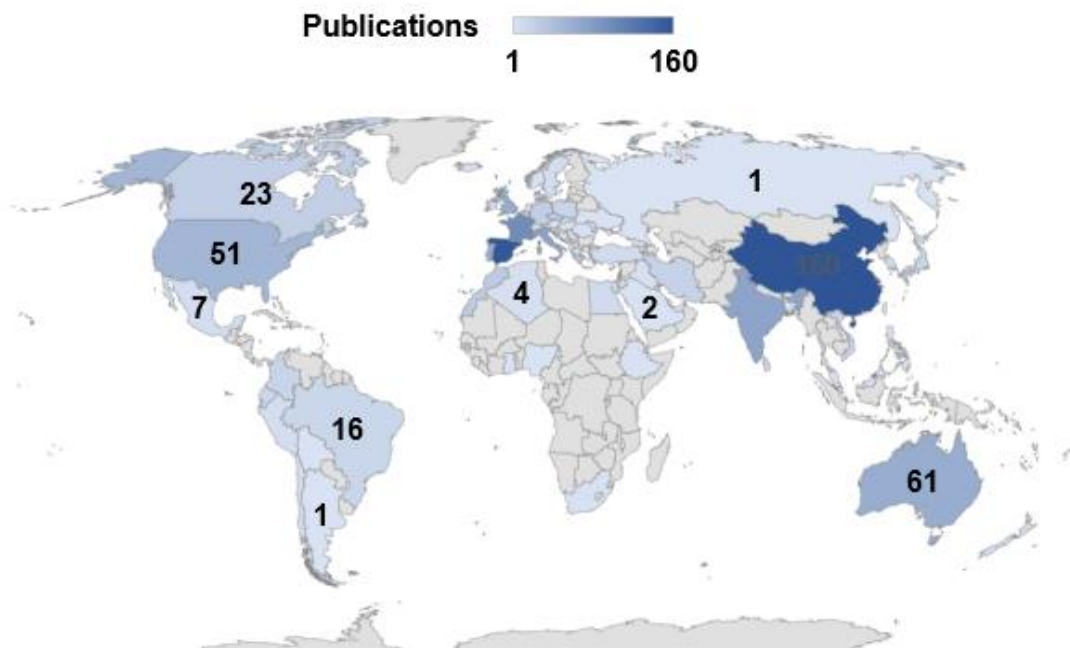


Fig. 4. Number of studies per country or territory in the rammed earth field: geographical overview

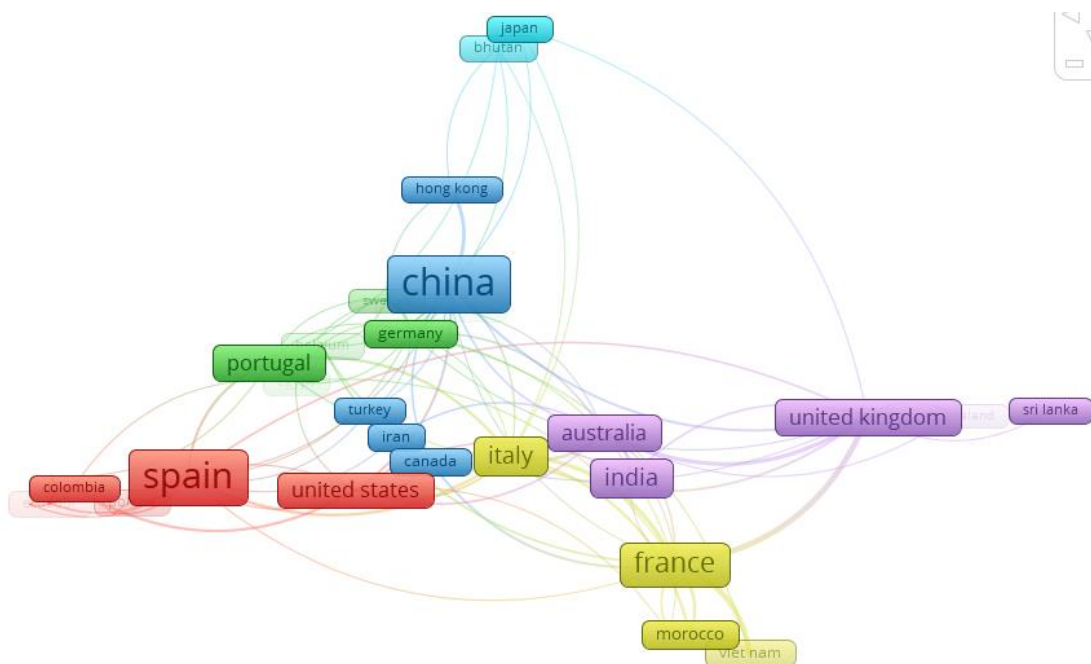


Fig. 5. Countries' co-authorship map by association strength by VosViewer

3.1.4. Contribution of educational institutions in rammed earth research

The bar chart (see Fig. 6) illustrates the total number of publications by the top 10 institutions across various disciplines from 2010 to 2024. Universitat Politècnica de València (Spain) is the biggest contributor to studies on rammed earth with 59 publications, followed by CNRS Centre National de la recherche scientifique (France) with 45 publications. In addition, although China is the largest contributor to rammed earth research with 160 publications, the leading Chinese institution ranks 10th worldwide with 25 publications, indicating that many universities and schools in China are interested in this subject area. In addition, only 3 countries namely Spain, France and Portugal jointly produced the 8 European educational institutions that are among the top 10 institutions in the world on the subject of rammed earth, demonstrates the role of funding and government policies in stimulating research.

3.1.5. Contribution of authors in rammed earth research

Table 3 shows the top 10 authors who contribute to the development of rammed earth research as a first author or co-author. Bui, Q.B., is the highest contributor in this field with 27 publications in the years 2010-2024. The second highest contributor is Morel, J.C., with 102 publications within the period under consideration; 24 of the articles published are related to rammed earth. While Oliveira, D.V., the third highest contributor, has 217 publications, 24 of which are on rammed earth.

Based on h-index, Oliveira has the highest h-index compared to other top 10 authors due to the number of publications and citations (6418 citations), followed by Venkatarama Reddy, B.V., with an h-index value equal to 37 and a total of publications and citations equal to 92 and 4553, respectively.

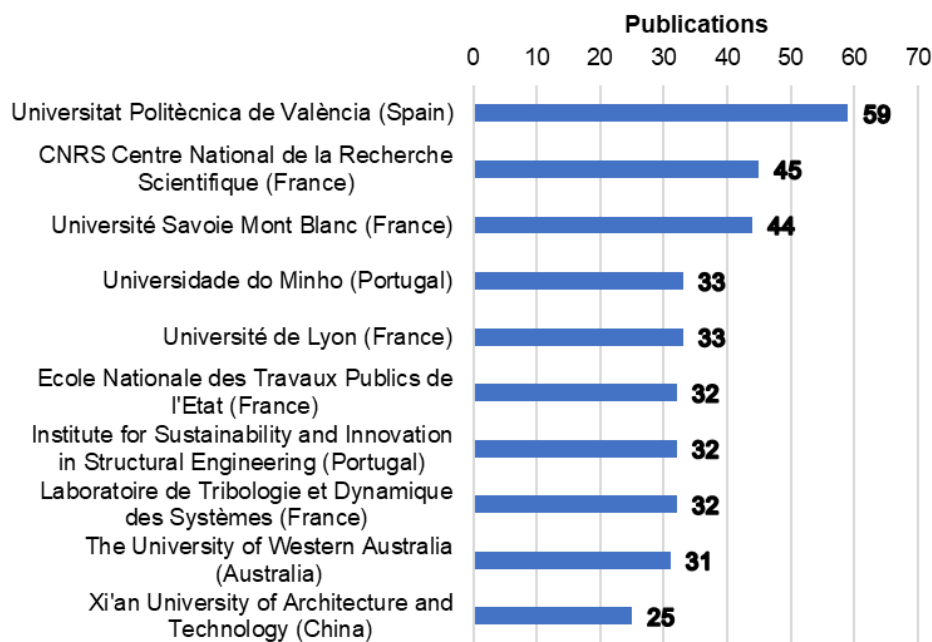


Fig. 6. Distribution of publications on rammed earth by educational institutions

Table 3. Research Impact and Productivity of Leading Authors in rammed earth

Author	Year of first publication	TP	TP in rammed earth*	h-Index	TC	Current affiliation (Country)
Bui Q.B.	2009	105	27	23	2467	Ton-Duc-Thang University (Vietnam)
Morel J.C.	1997	102	24	36	4594	Laboratoire de Tribologie et Dynamique des Systèmes (France)
Oliveira D.V.	2004	217	24	46	6418	Universidade do Minho (Portugal)
Mileto C.	2007	122	21	11	419	Universitat Politècnica de València (Spain)
Silva R.A.	2008	53	21	16	1054	Institute for Sustainability and Innovation in Structural Engineering (Portugal)
Fabbri A.	2004	114	20	25	2378	Laboratoire de Tribologie et Dynamique des Systèmes (France)
Ciancio D.	2005	43	19	17	1090	The University of Western Australia (Australia)
Venkatarama Reddy B.V.	1996	92	16	37	4553	Indian Institute of Science (India)
Tripura D.D.	2014	33	15	13	501	National Institute of Technology (India)
Zhou T.	2005	61	15	11	404	Xi'an University of Architecture and Technology (China)

TP= Total Publications, TC= Total Citations, *= TP in rammed earth research in 2010-2024.

3.1.6. Keyword analysis

Figure 7 depicts the network co-occurrence of all keywords (5749 keywords) related to rammed earth research between 2010 and 2024, as well as limited keywords to those with at least five occurrences (464 meet the thresholds) in order to restrict the keywords with the greatest total link strength. The size of the nodes corresponds to the number of occurrences of each of the 464 keywords. In addition, keywords are divided into seven clusters, and each cluster is given a specific colour to simplify analysis and show how different keywords are related.

Based on occurrence, “rammed earth” has the highest occurrence value of 549, which means it is a central and widely mentioned, being the main keyword. Furthermore, “walls (structural partitions)” with 262 occurrences, “compressive strength” with 180 occurrences, “sustainable development” with 155 occurrences, and “cement” with 78 occurrences are other keywords that appear frequently in the database analysed. Hence, these keywords are the most frequently discussed in the subject of rammed earth.

Total link strength is another significant parameter in the analysis of the database; “rammed earth” has the highest total

link strength value of 3952 of 33147 in this research. Moreover, “walls (structural partitions)”, “compressive strength,” and “sustainable development” also have high total link strength values of 2207, 1631, and 1200, respectively. These keywords also have the highest number of links to other keywords in the subject area.

3.1.7. Analysis of publication per earthen construction type

As previously stated, this study focused only on rammed earth. This paragraph provides an overview of the publications (articles and conference papers) on each type of earthen building, such as adobe, compressed earth block, wattle and daub, and earthbag, as well as the number of publications that investigated rammed earth with other types of earthen construction in Scopus from 2010 to 2024.

Based on the Fig. 8, rammed earth (RE), adobe (Ad), and compressed earth block (CEB) are the most studied types of construction in the field of earthen construction. The percentage of each field of these three genres relative to their total (sum of all three types) was determined using the following formula:

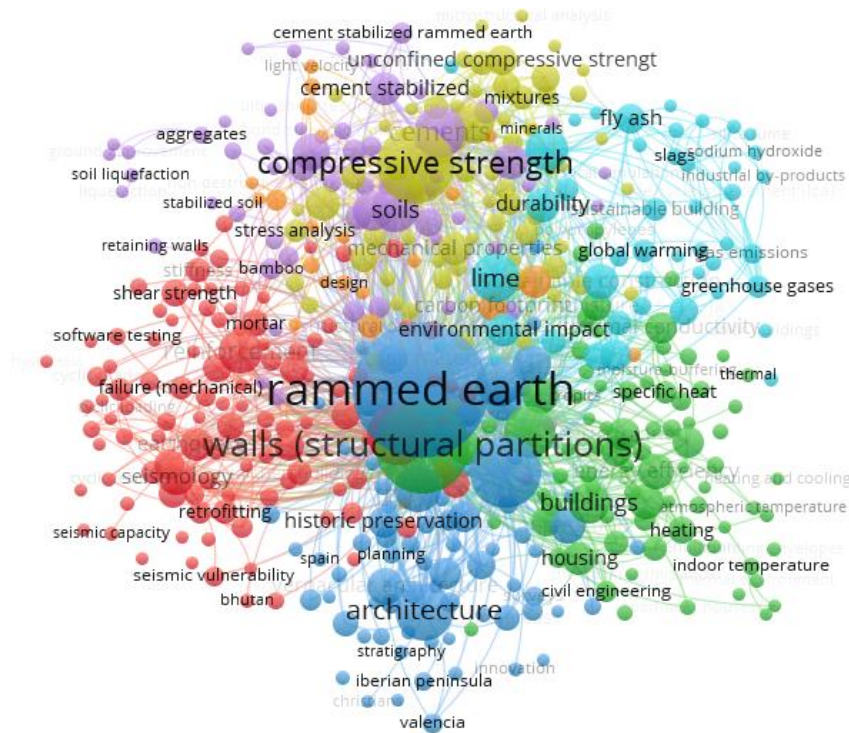


Fig. 7. The most crucial keywords used in publications on rammed earth

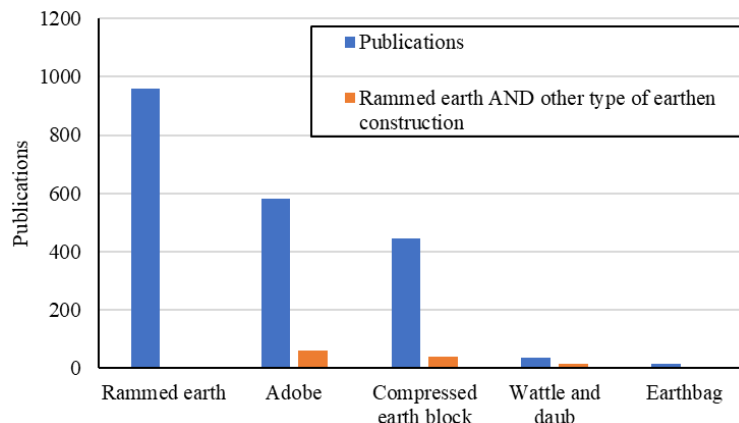


Fig. 8. Bibliographic production on each type of earthen construction

$$X\% = \frac{x}{RE + Ad + CEB} \quad (1)$$

X: type of earthen constructions.

Rammed earth accounted for 48.31% (close to half) of the overall total, representing the largest component of the distribution, followed by adobe, which contributed 29.29 %, and compressed earth blocks (CEB), which contributed 22.40%. As shown, rammed earth is the largest contributor in the area of earthen construction, which indicates why the authors concentrated on rammed earth in this publication.

3.1. Systematic literature review

3.1.1. Mechanical properties

- Compressive strength
 - Unstabilized rammed earth

Many researchers have studied the compressive strength of rammed earth by investigating the effects of stabilised and unstabilised rammed earth (URE) on the compressive strength. [28] indirectly studied the compressive strength through analysing the relationship between soil dosage and compaction. According to [28], the correction of the original soil provides a high value of compressive strength of 2.75 MPa without the need to utilise a stabiliser. [29] proposed an empirical equation that combines the ratio of fine elements (clay and silt) and compressive strength:

$$\text{Compressive strength} = -0.033\omega^2 + 0.376\omega + 0.297 \quad (2)$$

With ω being, the ratio of fine aggregates (silt and clay) to coarse aggregates (sand and gravel) is.

According to the equation above, the highest value was obtained with $\omega = 5.70$, indicating that the fines dosage should be 5.70 times the aggregate dosage. After replacing ω by 5.70, the highest value of compressive strength was 1.37 MPa. [29] presented a method that could inspire researchers to extend the strength formula for stabilized rammed earth (SRE).

Another element that affects compressive strength rating following a uniaxial compressive test is the form of the

specimens. The larger the specimens are, the more the values obtained are validated, and the better the result. Also, a cylindrical shape provides a higher strength value compared to cubic or prismatic shapes (see Table 4) [30]. In order to avoid inhomogeneity and the influence of the large particle size in the result, and to make specimens suited to the wall properties, [31] suggested using SRE to create cylindrical specimens that were at least three times bigger than the maximum size of the soil's particles. [32] recommended that the dosage and the largest diameters should follow the scale used in the model to obtain results of specimens with those of prototypes.

In most cases, the test procedure used to obtain the compressive strength of the earthen material involves conducting uniaxial compression tests. Some studies used the protocols employed to test the uniaxial compression test of unreinforced concrete, such as NF EN 12390-4, ASTM D1633-00, and EN 1015-11 [28,33,34], due to the nonexistence of a protocol for earthen construction.

- Stabilised rammed earth

Rammed earth can be made more stable by incorporating various stabilisers, including lime and cement, to enhance the mechanical properties of rammed earth. Even though the compressive strength of rammed earth is not an issue, it strongly affects the compressive resistance of RE. Rammed earth stabilised by cement can enhance the compressive strength to 5-10 MPa (see Table 4), which is 1.5 to 5 times higher than the URE strength [6,33,35,36]. This higher value is not only sufficient for resisting vertical loads but also improves its humid durability, which is another weakness of rammed earth.

Table 4 lists the different studies related to the compressive strength and Young's modulus reported in the literature.

Table 5 shows data extracted includes the minimum, maximum, and average values for compressive strength and young's modulus for URE and SRE, providing a comprehensive overview of the range and variability observed across studies. The variance of compressive strength is in the range of 1-2.75 MPa and 1.2-9.40 MPa for URE and SRE, respectively, while there is a significant dispersion in the Young's modulus, varying from 100 MPa to 1304 MPa and from 175 MPa to 1166 MPa for URE and SRE, respectively.

Table 4. Compressive strength and Young's modulus of unstabilized rammed earth URE and stabilized rammed earth SRE for different samples

Ref.	Sample shape	Size l x w x h [cm], ϕ , h [cm]	URE / SRE	Compressive strength [MPa]	Young's modulus [MPa]	Standard
[32]	Cylinder	15, 30	URE	2.07	-	-
[28]	Cylinder	15, 20	URE	2.75	133.51	NF EN 12390-4
[35]	Cylinder	10.4, 20	SRE (cement)	9.4	1166	-
[37]	Prism	30x30x80	URE	1.14	-	-
[33]	Cylinder	10.16, 11.64, 7.11, 14.22	SRE (cement)	3.70	-	ASTM D1633-00
[34]	Prism	16x4x4	URE	1.5	471	EN 1015-11
[6]	Cube	10x10x10	URE	1.74	-	-
			SRE (5% cement)	6.51	-	-
[38]	Cylinder	16, 32	URE	1.00	470	-
[39]	Cylinder	7.5, 15	URE	2.23	143	-
			URE	1.77	-	-
[36]	Cube		SRE (5% cement)	2.85	-	-
			SRE (10% cement)	4.79	-	-
			SRE (15% cement)	7.61	-	-

Ref.	Sample shape	Size l x w x h [cm], ϕ , h [cm]	URE / SRE	Compressive strength [MPa]	Young's modulus [MPa]	Standard
[30]	Cylinder	16, 30	URE	1.9	500	-
	Prism	40x40x20	URE	1	100	-
[40]	Cylinder	10, 20	SRE (5%lime)	1.20	175	-
	Cylinder	10, 20	SRE (4%lime + 4%cement)	4.8	355	-
	Cylinder	10, 20	URE	1.26	1034	-

Table 5. Min, max and average of compressive strength and young's modulus for URE and SRE

URE/ SRE		Compressive strength [MPa]	Young's modulus [MPa]
Min	URE	1.00	100
Max		2.75	1034.00
Average		1.67	407.36
CV		0.53	304.39
Min	SRE	1.20	175.00
Max		9.40	1166.00
Average		5.11	565.33
CV		2.48	431.05

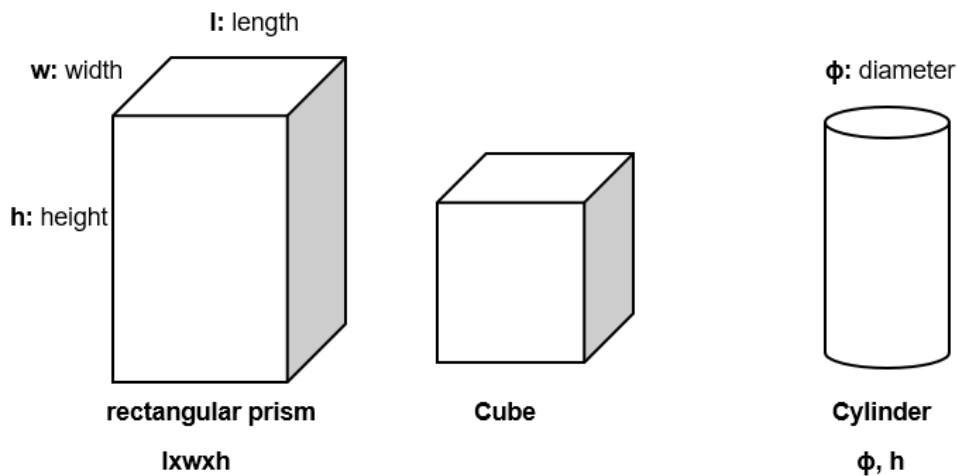


Fig. 9. 3D geometric shapes with dimensional notations

To provide a clear understanding of the specimens used in this study; Fig. 9 illustrates the different geometries and their corresponding dimensions. The specimens included a rectangular prism, cube, and cylinder, each defined by their respective measurements of length (l), width (w), height (h), and diameter (ϕ). These dimensions are crucial for understanding the scale and proportions of the specimens used in the analysis, ensuring consistency and accuracy in the experimental setup.

• Tensile strength

Tensile strength is one of the lowest mechanical properties of rammed earth, which makes it prone to earthquakes. It is influenced by testing methods, stabilisers, additives, and material composition. The value is generally too small in the range of 0.1-0.35 MPa [4]. According to [41], the addition of cement as a stabiliser enhanced the tensile strength to 0.77 MPa, and this value can reach 1.16 MPa with the combination of 3% coir fibre and 10% cement (see Table 6). In the absence of tensile strength test, it is recommended to take the tensile strength as equal to 10% f_c [42,43]. Similarly, reference, [30] was experimentally shown that the tensile strength was equal to 11% of the compressive strength, and the tensile strength of the layers and

interlayers (excluding the last layer) was investigated. It was found that the tensile strength was similar to that within the layers, which means that the wall has isotropic behaviour. [44] showed the influence of a combination chemical stabiliser (cement lime) and fibre reinforcement to tensile strength and durability, and it was found that the combination of 6% of chemical stabiliser with 0.75 fiber reinforcement provided the optimal tensile strength and durability (see Table 6). [45] showed that good compaction and a reduction in water content enhance the tensile strength of rammed earth independently of the kind of soil, and the tensile strength is in the range of 5-12.5% compressive strength, while it reaches 15-20% of the compressive strength for rammed earth stabilised by lime. Table 6 summarises the findings from various studies in the literature to understand the average tensile strength, its relationship with compressive strength, and the influence of stabilisers. The tensile strength exhibits a significant variation from 0.16 MPa to 1.16 MPa, and the ratio of tensile to compressive strength is in the range of 7%-20%.

Table 7 summarises the main strength property results extracted from Table 6.

Table 6. Tensile strength f_t , compressive strength f_c and ratio f_t/f_c for URE and SRE

Ref.	Sample l x w x h [cm] ϕ , h [cm]	Test	Stabilisers (%)	f_t [MPa]	f_c [MPa]	f_t/f_c [%]	Standard
[41]	10x10x10 (cube)	Tensile splitting	Cement (10)	0.99	6.5	15	IS 5816
			Cement (10) + coir fibre (3)	1.16	6.2	19	
			Coir fibre (3)	0.39	4.1	10	
[39]	7.5, 15 (Cylinder)	Tensile splitting	Cement (2.5)	0.30	2.80	11	-
			Cement (5)	0.47	3.70	13	
			Cement (7.5)	0.61	4.46	14	
			Cement (10)	0.77	5.2	15	
			Fibreglass (0.75)	0.44	2.14	21	
			Fibreglass (1.5)	0.53	2.5	21	
			guar gum (2.5)	0.27	2.64	10	
			Unstabilised	0.24	2.23	11	
[46]	10, 20 (Cylinder)	Tensile splitting	Unstabilised	0.38	2.03	19	-
			Cement (6)	0.44	3.24	14	
			Lime (4)	0.40	2.15	19	
			Barley fibre (0.75)	0.50	2.74	18	
			Palm fibre (0.75)	0.46	3.25	14	
[30]	16, 30 (Cylinder)	Tensile splitting	Unstabilised	0.24	2.18	11	-
			Cement (10)	0.47	4.3	11	
[45]	5 (4.5 medium), 14 (Cylinder)	Direct tensile	Unstabilised	0.24	-	5-12.5	-
[45]	5, 5 (Cylinder)	Tensile splitting	Unstabilised	0.30	-	5-12.5	JGS 2551-2009
[29]	3.9, 8 (Cylinder)	Tensile splitting	Unstabilised	0.22	1.04	21	ASTDM D 2166
			Cement (4)	0.32	4.43	7	
			Cement (7)	0.39	5.31	7	
			Cement (10)	0.43	5.98	7	
			Cement (7) + Waste Tire Textile Fiber (1)	0.73	6.2	12	
[47]	7.1, 14.2 (Cylinder)	Tensile splitting	Cement (7) + Waste Tire Textile Fibre (4)	0.89	5.15	17	ASTM D885M- 10A
			Waste Tire Textile Fibre (1)	0.43	4.01	11	
			Waste Tire Textile Fibre (4)	0.68	3.32	20	
			Unstabilised	0.27	3.8	7	
			[44]	10, 20 (Cylinder)	Tensile splitting	Unstabilised	

The results obtained from the literature showed a diversity in the value of tensile strength of rammed earth due to the existence or absence of chemical stabilisers and fibres (textile or natural). Literature also showed the diversity in the estimation percentage between tensile and compressive strengths. This range of diversity values is noted to be low (7%–15% with an average of 11%) in the case of chemical stabilisation (cement or lime). Meanwhile, this ratio (f_t/f_c) ranges from 12% to 19%, with an average of approximately 14% in URE (see Table 7). The ratio was in the range of 10%-20% for fibre reinforcement with an average of 15%, while the combination of chemical stabilisers and fibres provided a ratio of f_t/f_c between 12-19% with an average of 15% (see Table 7).

Hence, the presence of chemical stabilisers (cement and lime) can enhance the tensile strength but not with the same effect

on compressive strength, which makes the ratio f_t/f_c lower. The combination of chemical stabilizers with fibers provided the best enhancement of tensile strength (high value of f_t/f_c), and this combination could provide an optimum tensile strength, even though the percentage of chemical stabilizer is not high. As a result, it is necessary to modify the approximate percentage of tensile strength found in the literature. Figure 10 illustrates that the tensile strength increases with the increase of compressive strength, despite notable variability, and the increase is higher and greater in the stabilized rammed earth by fibers or a combination of fibers and chemical stabilizers compared to unstabilised rammed earth and chemically stabilized rammed earth.

Table 7. Comparison of strength properties of unstabilised rammed earth URE and stabilized rammed earth SRE

Stabilised RE /Unstabilised RE		f_t [MPa]	f_c [MPa]	f_t/f_c [%]	Mean (f_t/f_c) [%]
Min	Chemical Stabilised	0.30	2.8 ^[1]	7	11
Max		0.99	6.50 ^[1]	15	
Average		0.51	4.37	12	
CV		0.198	1.273	-	
Min	Fiber reinforcement	0.27	2.64 ^[1]	10	15
Max		0.68	3.32 ^[1]	20	
Average		0.46	3.09	15	
CV		0.110	0.663	-	
Min	Chemical Stabilised + Fibre reinforcement	0.73	6.20 ^[1]	12	15
Max		1.16	6.20 ^[1]	19	
Average		0.93	5.85	16	
CV		0.177	0.495	-	
Min	Unstabilised + unreinforced	0.16	1.30 ^[1]	12	14
Max		0.38	2.03 ^[1]	19	
Average		0.26	2.10	12	
CV		0.060	0.883	-	

^[1] min and max value f_c are related to the value of f_t .

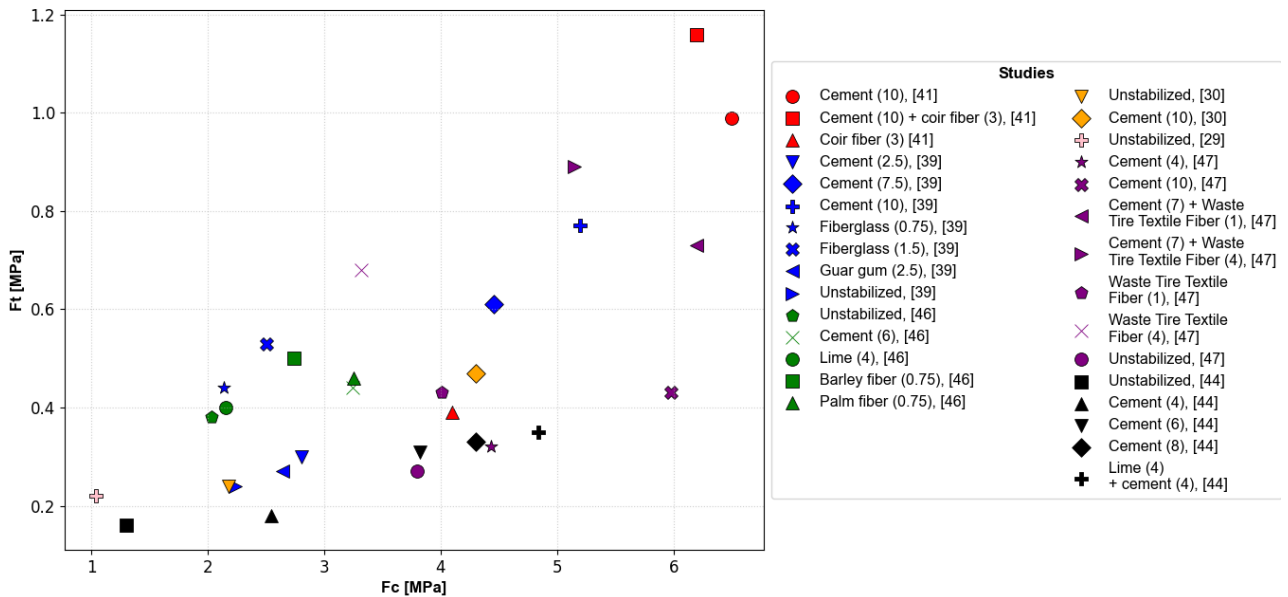


Fig. 10. Tensile and compressive strength in previous studies

The researchers in this study used the information of Table 6, which contains 30 data points, to develop a polynomial Eq. (3) with a degree of 2 to estimate the value of tensile strength as a function of the percentages of chemical stabilizers and fibers (polynomial with two variables). Unlike empirical formula for estimating the tensile strength using the compressive strength value [42,43], this method utilizes the percentages of chemical stabilizers and fibers.

$$T(f, s) = 0.252 + 0.198f + 0.028s - 0.035f^2 + 0.009sf + 0.001s^2 \quad (3)$$

with: f : percentage of fibres in (%), s : percentage of chemical stabilisers in (%)

The polynomial above has been achieved based on the hypothesis:

- The percentage of chemical stabilisers and fibres is no more than 10% and 4%, respectively.
- Chemical stabilisers are lime and cement without separating their percentage.
- The same applies to fibres without considering the kind of fibre, natural or textile.

Statistically, the coefficient of determination is $R^2=0.69$, and the strong correlation is $r=0.83$, which means that the chemical stabilisers (s) and fibre stabilisers (f) have a strong positive link with the prediction model of rammed earth tensile strength (see Table 8). This indicates that the model is practically useful for the quality control of rammed earth in terms of mechanical

strength and conception design, although field verification remains necessary to account for the 31% unexplained variability. In addition, the mean absolute error (MAE) is 0.159 MPa, indicating that the tensile strength prediction deviates by an average of 0.159 MPa. The mean absolute percentage error (MAPE) is 20.41%; hence, the prediction is off by 20%. Based on the percentage error of prediction values and the average of real ones (see Table 9), it is under 10% (good) in 8 points, and 6 of them are under 5% (very good); it is under 30% in 7 points (acceptable); and it is up to 30% in only 2 points. Consequently, most errors fall under the MAPE, except for a few failures in 4 predictions. The highest errors occur when the percentage of chemical stabilisers is below 2.5%, and fibre stabilisers exceed 2%.

Mathematically, the higher percentage of the chemical stabilisers, the higher the value of the tensile strength 'T' obtained from the polynomial (see Fig. 11). However, the chemical stabilisers should not exceed 10% in the composition

of rammed earth to avoid reducing its thermal performance and enhancing its CO₂ emissions, thus reducing its environmental features as an eco-friendly status.

On the other hand, fibres could enhance the value of tensile strength obtained from the polynomial until reaching an optimum (f_{opt}), then the fibres will have a negative impact on the tensile strength (see Fig. 11). The fibres provide a restriction to this prediction in the absence of chemical stabilisers due to the variability in the strength of the fibres, which are very different. For instance, 2.5% of fibres without chemical stabilisers predict a tensile strength of 0.53 MPa, which is significantly high, while the literature records that the tensile strength of rammed earth with 2.5% guam gum is 0.27 MPa [39], and the percentage error is 95.6% (see Table 9), and this variance is the highest compared to other literature points. Consequently, it is imperative to exercise caution when relying solely on this method, as it may overlook the specific mechanical properties of fibres, particularly when no chemical stabilisers are employed.

Table 8. Thumb rule for deducing the strength of statistical correlation between the variables [48]

Absolute value of coefficient of correlation (r)	Strength of correlation
$0.68 \leq r \leq 1$	Strong
$0.36 \leq r \leq 0.67$	Moderate
$r \leq 0.35$	Weak

Table 9. The percentage error between the mean of experimental values and the predictive model and its performance indices

Fibers (%)	Stabilizers (%)							
	0	2.5	4	5	6	7	7.5	10
0	1.7%	9.4%	5.6%	11.3%	3.6%	27.4%	15.0%	5.0%
0.75	18.4%	-	-	-	-	-	-	-
1	3.5%	-	-	-	-	1.0%	-	-
1.5	11.3%	-	-	-	-	-	-	-
2.5	95.6%	-	-	-	-	-	-	-
3	36.2%	-	-	-	-	-	-	1.8%
4	28.8%	-	-	-	-	10.2%	-	-
R ²	0.69							
MAE	0.159							
MAPE	20.41%							

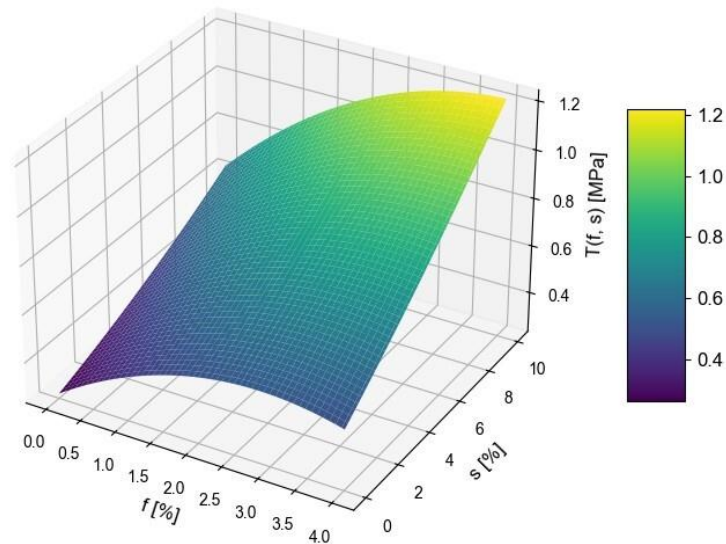


Fig. 11. Visualization of polynomial T(f,s) in 3D

• Shear strength

The seismic performance depends on shear strength, which is low in the case of rammed earth. Rammed earth exhibits a shear strength in the range of 0.15-0.85 MPa. While some regulations treat the shear strength of rammed earth, the Australian Handbook [49] assume it to be zero, [50] approximates it to be nearly zero, specifically 0.0024 MPa, for rammed earth, whereas [42] estimates a shear strength of 0.08 MPa in the absence of a compression or shear test. These changes show how each code handles near-zero shear capacity differently, and highlight the brittle behaviour of rammed earth under shear loads. However, if the value of compression strength is available, the shear strength is assumed to be equal to 7% of compression strength ($f_{shear} = 0.07f_{compression}$) [42,43], while [30] assumed to be equal to 10% of compression strength. Various studies have focused on the seismic behaviour of rammed earth by analysing its shear parameters, such as the friction angle and cohesion. [51,52] studied the mechanical behaviour of interlayers (layer interface or interface between two successive layers) and layers of rammed earth, and the result demonstrated that shear strength at interlayers was 78%-91% of intralayers. [52] is one of the few researchers who studied the full-scale shear test and took into account interlayers, unlike small-scale tests that have only one layer and neglect the behaviour of interlayers, which is not ideal in the case of a full rammed earth wall. [34] studied the

shear behaviour of rammed earth reinforced by reinforced textile mortar. The study found that the nylon fibre mesh and glass fibre mesh increase the shear strength of rammed earth, and promote stress distribution after cracking, which positively affects its seismic capacity. This reinforced solution is a suitable solution for vernacular rammed earth heritage, and it needs further investigation to understand the shear behaviour of reinforced rammed earth. [53] studied the mechanical behaviour of different kinds of earthen materials (earth block masonry, rammed earth, and cob) and compared their behaviour. The shear behaviour, like all other mechanical properties, is higher for rammed earth compared with other earthen materials. Table 10 summarises the outcome of studies conducted by some researchers on the shear properties of rammed earth. Studies in Table 10 indicate that shear modulus is from 251 MPa to 695 MPa, except for one study that showed a high value compared to others. Notably, only investigations employing the diagonal compression test have determined the shear modulus. Shear strain varies from 0.003 to 0.031, and the highest values are reached by reinforced rammed earth, except for a single unreinforced wall. This suggests that reinforcement enhances the stiffness of rammed earth. In addition, only diagonal compression and direct shear box methods have been utilised to investigate shear strain. There are limited studies and investigations that focus on the direct shear box and shear parameters. For this reason, the next paragraph analysed previously published papers in these parameters.

Table 10. Shear strength, shear strain and shear modulus for reinforced, unreinforced and unstabilised rammed earth

Ref.	Wall size H x w x t [cm]	Shear strength [MPa]	Shear strain ϵ_{max}	Shear modulus [MPa]	Test
[34]	Unreinforced rammed earth (55x55x20)	0.08	0.003	251	Diagonal compression
[34]	Nylon fiber mesh (NRE) (55x55x20)	0.1	0.031	695	
[34]	Glass fiber mesh (GRE) (55x55x20)	0.1	0.007	418	
[30]	Unstabilized rammed earth (100x100x30)	0.18	-	-	Monotonic test (in plane shear capacity)
[54]	GSRE (2.5%) (55x55x20)	0.14	0.0056	576	Diagonal compression
[54]	GSRE (5%) (55x55x20)	0.14	0.0095	505	
[54]	GSRE (7.5%) (55x55x20)	0.18	0.012	620	
[55]	Unstabilized rammed earth wall (250x200x50)	0.04	-	315	Diagonal compression
[52]	Unstabilized rammed earth wall (50x50x45)	0.23	0.022	-	Direct shear box
[56]	Unstabilized rammed earth URE wall (250x180x40)	0.02	-	-	Cyclic test (in plane shear capacity)
[57]	Unstabilized rammed earth URE wall (50x50x10)	0.7	-	1582	Monotonic test (in plane shear capacity)
Min		0.04	0.003	251	
Max		0.7	0.031	1582	
Average		0.17	0.013	620.25	
CV		0.18	0.008	456.54	

NRE: Nylon fiber mesh rammed earth, GRE: Glass fiber mesh rammed earth, GSRE: granite soil rammed earth.

• Cohesion and friction angle

Cohesion C and friction angle ϕ are the main parameters that characterise the soil behaviour. Thus, several research projects are interested in these parameters, not only for earthen buildings but also for geotechnics. In earthen construction, the friction angle and cohesion directly influence the shear strength [58,59]. The literature experimentally shows that cohesion can be obtained as a function of compressive strength; the cohesion of the earthen layer can be assumed to be 10%-14% of the

compressive strength of the earthen layer [30,51]. On the other hand, [57,60] estimate cohesion C as a function of tensile strength and in the range of 1.5-2. [51,52,59] studied the relationship between the cohesion and friction angles of intralayers and interlayers at full scale. [51] reported that interfaces have little effect on vertical charges but have a significant effect on horizontal and diagonal charges. In addition, the features of the interface were 85% of those of the equivalent earthen layer. Unlike, [52,59] recorded that the

friction angle is consistently maintained across both interlayer and intralayer sections of a layer, with the ratio of intralayer to interlayer friction angle being 93%. In contrast, cohesion varies based on the layer's position, whether it is in the upper, middle, or lower part of the earthen layer. Notably, there is an approximate 20% difference between the interlayer and intralayer cohesion within the earthen layer. This variation in the cohesion of an earthen layer depends on suction (compaction and geometry), unlike the angle of friction, which depends on grain type. Therefore, as the layer thickness increases, the variation in cohesion among the different parts of the layer also increases, which demonstrates how cracks propagate in the interlayers of the earthen wall during seismic loading. Conversely, [57] found that cohesion (c) and layer thickness had a limited effect on the shear behaviour, whereas the interface tensile strength (ft) and friction angle (ϕ) influenced it.

Similar to other mechanical properties, the density and the integration of cement as a stabiliser affected the mechanical properties. [61] concluded that increased density significantly enhances cohesion while leaving the friction angle unaffected. According to [62,63], cohesion increases with the integration of cement, but the angle of friction remains relatively stable and less sensitive to changes in the mixtures compared with unstabilised rammed earth. [62,64] showed that alkali-activated fly ash (AAFA) has the ability to boost cohesiveness and dissipated energy in both situations in combination with a low portion of cement or without (only AAFA as stabilizer), and its cohesion is higher than that of cement stabilization without the inclusion of AAFA, providing a sustainable substitute for conventional cement stabilization, while it does not show any effect on the friction angle. [65] showed that minerals such as sodium sulfate and calcium chloride decrease the compressive strength and cohesion, but the friction angle remains unchanged.

3.1.2. Thermal characteristics

Rammed earth is encouraged as a main green building material because of its high thermal efficiency compared to conventional materials. The high thermal mass of rammed earth

makes it a suitable material for absorbing heat during the day and releasing it at night, leading to a stable indoor temperature. This thermal characteristic reduces the need for artificial heating, cooling, and ventilation, which minimises the energy consumption [66]. In addition, the high thermal mass of rammed earth makes it a fit material in hot and arid climates [67,68]. Thermal conductivity is another parameter that distinguishes rammed earth because it is lower than that of conventional materials. Conductivity depends on the moisture content, soil grading, stabilisers, and additives.

Similar to the mechanical characteristics, the moisture content negatively affects the thermal resistance of rammed earth. [69] showed that a moisture content of 2 % reduced the conductivity by 30%, while a moisture content of 5 % reduced the conductivity by 75% in a dried state. [70] found a linear variation between water content and conductivity, as well as a coefficient that depends on soil characteristics, which can be empirically calculated for different water contents and dried states. Relative humidity is another factor that enhances the conductivity of rammed earth [70]. [71] found the same results regarding the linear variation between water content and conductivity, and also studied the case of rammed earth stabilised with 6% CEM II Portland cement, as well as the effect of soil grading. The findings indicated that the highest percentage of sand improved the value of thermal conductivity.

Generally, unstabilised rammed earth has better thermal and acoustic performance than stabilised rammed earth, which has higher shear and tensile strengths [4]. However, this conclusion is not usually correct. For instance, date palm spathe fibres positively affect the thermal performance of rammed earth, and the thermal conductivity decreases linearly [72]. The addition of xanthan gum biopolymers has the potential to replace chemical stabilisers (cement and lime), especially because it does not affect thermal conductivity [73].

Compaction pressure also influences the thermal conductivity. [74] has reported that pressure compaction enhances the conductivity value, and stabilised rammed earth with fly ash has a lower thermal conductivity than unstabilised rammed earth.

Table 11. Thermal conductivity and density for URE and SRE in different samples

Ref.	Stabilizer [%]	Conductivity [W/mK]	Density [Kg/m ³]
[72]	Unstabilized	0.514	2985.18
[72]	Date palm spathe fibers (2)	0.405	2758.85
[72]	Date palm spathe fibers (5)	0.274	2319.25
[73]	Xanthan guan biopolymer (1.5)	0.53	-
[73]	Xanthan guan biopolymer (1)	0.52	-
[73]	Xanthan guan biopolymer (0.5)	0.50	-
[73]	Unstabilized	0.48	-
[75]	Unstabilized	0.46-0.81	1700-2200
[76]	Unstabilized	0.6-1.1	1800-2200
[77]	Unstabilized	0.82-1.6	2400
[78]	Unstabilized	1.483 ¹	2194 ¹
[78]	Unstabilized	0.618 ²	1610 ²
[74]	Unstabilized	0.64	2158
[74]	Fly ash (25)	0.52	2049
[79]	Soil (92.5) + Rice husk ash (7.5) + cement (10)	0.65	1600-1700
[79]	Soil (100) + Rice husk ash (0) + cement (10)	0.80	1850-1950

¹Min value of conductivity and density ²Max value of conductivity and density

In order to better illustrate the data collected in Table 11, the plot in Fig. 12 shows the variety of thermal conductivity and density in different studies from 2010 to 2024. Most of the studies (see Fig. 12) recorded that density is in the range of 1600-2400 Kg/m³ except unstabilised rammed earth and rammed earth stabilised with 2% of date palm fibres that recorded 2985.18 and 2758.85 Kg/m³, respectively [78], while materials based on biopolymers often have inferior conductivity and density. Hence, the conductivity of stabilised materials, such as fly ash and rice husk composites, is comparatively mild.

3. Discussion

In the dynamic realm of rammed earth, the bibliometric analysis and systematic literature review (SLR) detailed independently in this paper present a comprehensive approach. The findings illustrate the development and growth of publications on the use of rammed earth construction as a crucial sustainable construction material.

3.1. Trends in publications and geographic distribution

Most studies on rammed earth were published since 2012, when climate change became a significant issue worldwide and mitigating its consequences was required. Thus, rammed earth became a significant green building material with low embodied energy and carbon dioxide emissions. China and Western European countries (France, Spain, Portugal, and Italy) are the biggest contributors to rammed earth studies because they have developed infrastructure research in this major, climate change mitigation policies, as well as several earthen heritage buildings located. Even though Western European countries and China have many publications in the study of rammed earth, there is no developed rammed earth code or standard that focuses on this genre of building material. Australia, in 2002 and New Zealand, in 1998, and 2024 (update), published codes on rammed earth despite the number of published articles on the subject from these two Oceania countries being 61 for Australia and 6 for New Zealand. In addition, weather is a significant factor that influences geographical distribution because rammed earth is sensitive to humidity and water, and it is not an ideal solution in countries where the weather is snowy or very cold, and the annual rainfall is high. Therefore, the geographical distribution of publications is limited to countries with hot and arid climates [80].

In MENA, there is a gap in research on rammed earth and its influence on climate change, despite the fact that these countries have many natural resources and several historical edifices that were built from earthen materials. Also, many of these countries (Iran, Algeria, Egypt, Syria, Lebanon, and Morocco) are located in zones with high seismic hazards, making the study of rammed earth important. The earthquake crisis presents not only a challenge but also a valuable opportunity to investigate rammed earth to update and create national regulations, similar to the actions taken by Iran after the Bam earthquake in 2003 [81], when several studies focused on the mechanical and seismic behaviour of earthen construction, particularly adobe, which is more widely used. Iran is not an exception; Nepal has conducted extensive research on rammed earth, enabling it to develop its own building code in 2015 [82], an improvement upon its initial version released in 1995. However, from 2010 to 2024, Nepalese institutions have only published four indexed works, such as articles and conference papers, on rammed earth, showing that a lot of research on this topic is not listed in the Scopus and Web of Science databases.

In addition, numerous developing countries lack established infrastructure or standards for rammed earth construction. Nevertheless, they continue to use this technology traditionally, despite having a significant number of historical monuments made from rammed earth specifically or earthen buildings in general that require restoration.

3.2. Trend and findings in rammed earth and other keywords and scope

Rammed earth or any other earthy material is chosen for construction primarily because of its low embodied energy and greenhouse gas emissions. Its large thermal mass and low thermal conductivity allow for the absorption, storage, and release of heat gradually. Due to these environmental and thermal advantages, it is required to investigate its mechanical properties. An imbalance exists in the mechanical literature, which focuses on studying compressive strength as a primary factor and the behaviour under different parameters, including but not limited to clay content, moisture content, and stabilisers. Few studies have investigated the shear and tensile strengths. This disparity is a significant problem because tensile and shear failures are the weaknesses of rammed earth, and they directly influence the seismic capacity of rammed earth walls. Unlike the compression of rammed earth, it is sufficient for single-story and double-story buildings and is more gradual and predictable.

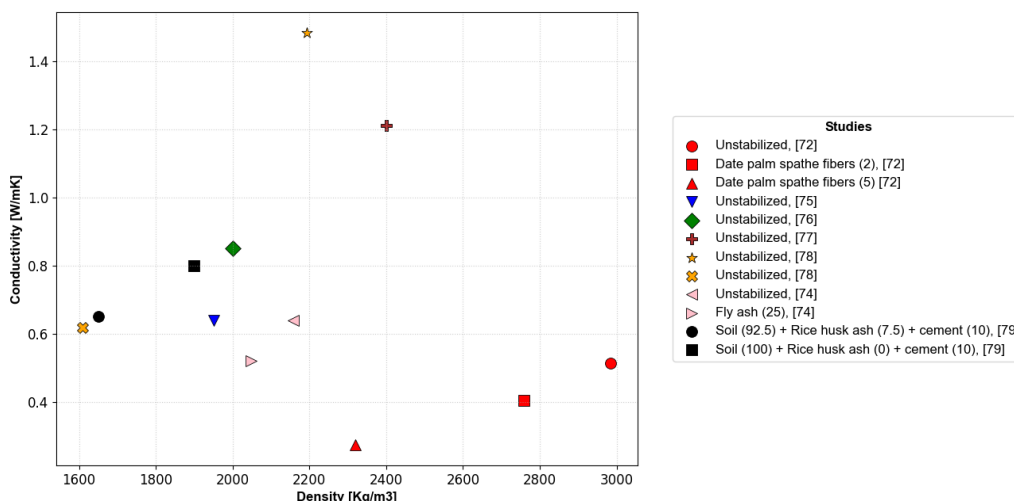


Fig. 12. Variation of thermal conductivity and density in different studies

The seismic performance of rammed earth, even though, seismic performance is low investigated due to several reasons;

- a. Lack of required tools.
- b. Challenges related to analysing a prototype in full-scale (expensive and complex).
- c. Seismic test options are limited to a small shaking table in the best situation or the use of indirect analysis (e.g., diagonal compressive test).
- d. Lack of seismic design standards for rammed earth.

In addition to mechanical properties, stabilisers are also the most trending keywords that were studied in previous publications, especially cement, lime, and fly ash, as well as reinforcements such as textiles and bamboo.

In summary, the variance of rammed earth strengths comes from the fact that several inner parameters influence the mechanical properties of rammed earth, including density, moisture content, and soil composition, as well as external parameters, such as the integration of mechanical stabilisers (compaction), fibres, and chemical stabilisers, which makes it challenging to control the mechanical and seismic behaviour of rammed earth. In contrast, concrete is easy to regulate since it is homogenised and has few variables, which makes it more suitable to use compared to earthen construction.

3.3. Future approach in rammed earth research

Table 12 summarises the previous and future trends in the area of rammed earth. As shown in Table 12, the authors moved from studying rammed earth as a traditional material used in historical monuments and studying it from a restoration perspective to utilising it as a sustainable material to mitigate climate change, owing to its higher environmental benefits. This change freed the authors from the constraints of treating rammed earth walls solely as historical monuments that warrant preservation of their architectural characteristics, allowing them to be considered as modern construction materials that can effectively compete with conventional building materials in contemporary applications. The interest is more oriented toward the mechanical properties and the influence of other materials on the mechanical behaviour of rammed earth. Future research should explore the use of ecological and local materials, as well as innovative approaches, to improve the mechanical and hydric performance of rammed earth. Hydric performance is another weakness of rammed earth that influences the mechanical properties negatively and makes the walls brittle.

Table 12. A thorough examination of rammed earth: recent studies and future approach

Aspect	Findings	Trends	Future approach
Publications	A number of studies have been published since 2012. The average number of publications from 2010-2024 is 64 publications.	2010-2014: Most of the publications were exploratory, related to historical buildings, mechanical, thermal, durability, and hygrothermal properties of rammed earth, especially URE. 2015-2019: Expansion into chemical stabilisation techniques, thermal performance, and the use of fibre reinforcement, as well as several studies in seismic performance. 2020-2024: more studies in seismic performance, growth in computational modelling, a combination of stabilisers, and investigation on tensile strength, as well as a significant number of publications on reinforcement.	More studies in the integration of bio-sourced material, 3d- printed, new mathematical approach, and machine learning. Further articles related to shear and tensile strength are mandatory.
Journals	“Construction and Building Materials” is the most periodical, followed by “Advanced Materials Research” and International Journal of Architectural Heritage.	Except for “Construction and Building Materials”, which published about one-tenth of the total publications. There is extensive variation in periodicals, and the total number of publications and journals is too limited.	Further investigation on emerging methods and technologies in rammed earth. Indexing journals should be more open to accepting articles related to rammed earth with encouragement for a special issue.
Countries	Major contributors are China, France, Spain, and Portugal.	Limitations in the contribution from different nations in the field of rammed earth. Limitations of collaboration among countries in the scientific production of the rammed earth area.	Contribution among nations, especially between developing and developed countries
Authors	Bui, Q.B., Morel, J.C., and Oliveira, D.V. are prominent contributors on rammed earth.	Multiple research interests for authors that have been working on rammed earth with more interest in engineering, materials science, arts and humanities and environmental science and energy	The contribution of researchers from different educational institutions and majors, especially computer science, mathematics, chemistry, and nanotechnology, could enhance the quality and number of publications.
Keywords	The main keyword is “rammed earth”. Other significant keywords are “compressive strength”, “sustainable development”, “cement”, and “lime”.	The primary motivation for using rammed earth in the construction sector is its contribution to sustainable development and a circular economy. Among the mechanical properties, compressive strength is the primary property examined by researchers owing to the compacted nature of rammed earth. Stabilisers (cement and lime) positively influence the mechanical and durability properties of rammed earth structures.	Bio-sourced material, nano-clay, 3D- printed, and textile-reinforced deserve further investigation to enhance mechanical performance, particularly tensile and shear strength.

4. Conclusion

Rammed earth is the oldest green building material and is crucial for modern sustainable construction. The bibliometric analysis of rammed earth from 2010 to 2024 showed a significant evolution in the number and quality of publications and a shift from discovering studies related to historical buildings, mechanical, thermal, durability, and hygrothermal properties of rammed earth, particularly unstabilised rammed earth URE (2010-2014), to chemical stabilization techniques, the use of fiber reinforcement, and their impact on mechanical performance (2015-2019), to a critical focus on seismic performance and how to enhance it by reinforcement and fiber stabilizers (2020-2024). While the number of publications in the Scopus database is limited, this does not imply a scarcity of contributions in this field, because many conferences that focus on earthen constructions are non-indexed, such as TERRA conferences, Seminario Ibero-Americano de Arquitectura y Construcción con Tierra (SIACOT) and the International Conference on Architecture & Construction with Earthen Materials, and articles have been published in non-indexed journals.

However, previous studies on this earthen material technology showed that compressive strength is a frequent mechanical keyword because of the nature of rammed earth, which is based on compacting earthen layers, and the compressive strength is sufficient for low-rise buildings (single-story or double-story). The tensile and shear strengths were low, with average values of 0.27 MPa and 0.23 MPa, respectively. The use of stabilisers enhanced the average tensile and shear values by 76.7% and 67.6%, respectively. Unlike the regulations [42,43,83] that consider the tensile strength to be equal to 10% of the compression strength, the experimental studies on tensile strength by direct tensile test or splitting tensile test found that the tensile strength could be taken as approximately 10%-15% in the case of unstabilised rammed earth and 15%-20% in the case of stabilised rammed earth. The combination of cement and vegetable fibre as a stabiliser could be the best technology to achieve a high tensile strength value. Further studies are required to optimise these factors and develop reliable methods for predicting and improving the tensile strength of rammed earth structures.

Since rammed earth has a high thermal mass and low conductivity, its thermal performance is the primary factor in choosing it over traditional concrete. The latter is in the range of 0.48-1.6 W/mK, and it is also influenced by the existence or nonexistence of stabilisers, such as cement, lime, and natural fibres, which were used not for enhancing thermal resistance but for boosting its mechanical or earthquake resistance.

Finally, rammed earth is a vital material that still requires further research to understand its mechanical behaviour and develop innovative standards and codes, as well as integrate nanotechnology, machine learning, 3D printing, and artificial intelligence.

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