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Anti-friction system for compression testing of rammed earth samples with a slenderness ratio of 1

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Abstract

The rammed earth construction method, a reversible natural resource, is an ancient technique that has enabled many buildings to survive for centuries. Although this technique is attracting much interest from scientists, the number of laboratory tests that characterise its mechanical performance currently remains limited. This article presents an anti-friction device, which allows unconfined compression tests on samples with a small slenderness ratio and saves a considerable amount of time in sample production, thereby facilitating the characterisation of earthen materials. The results obtained from the compression tests demonstrate the effectiveness of the use of a simple, reproducible laboratory protocol for determining the compressive strength of a rammed earth sample.

Keywords: Rammed earth samples, Compression test, Anti-friction system, Slenderness, Laboratory protocol.

1 Introduction

Due to its harmful effects on human communities and ecosystems, global warming is one of the most serious environmental problems facing the world today [1]. The construction sector is responsible for a significant level of pollution, as many building materials (concrete, cement, red bricks, blocks) use large amounts of energy in their manufacture and transport [2]. Most of this energy comes from burning fossil fuels, which increases CO_2 emissions into the atmosphere, contributing to global warming [3].

One solution to this problem is the use of local building materials. In fact, they result in a substantial reduction in environmental impact compared to the manufacture and sourcing of materials from distant locations and transporting them to the construction site as investigated by Morel et al. [4]. As described in a report [5], "local" suggests proximity and cost efficiency, while "material" implies a raw resource requiring processing and offering potential for reuse or recycling. Among local building materials, there is a raw earth construction technique known as Rammed Earth (RE). This process involves layering wet soil, in thicknesses of 8 to 15 cm, into formwork and compacting it using a dynamic impact method [6].

Over the past decade, this technique has attracted renewed attention within the scientific community [7]. As a result, a growing number of mechanical investigations have been conducted, relying on a wide range of manufacturing, conditioning, and testing procedures. This has led to significant variability in experimental approaches. In the absence of standardised protocols, this diversity of practices makes the comparison and interpretation of results particularly challenging. In this context, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures, known as "RILEM" plays a key role in structuring and advancing research activities. Two RILEM Technical Committees (319-MAE and 274-TCE) have been dedicated to enhancing the understanding and standardisation of raw earth as a construction material by conducting research, producing state-of-the-art reports, publishing technical recommendations, and organising international exchanges. Their main objective is to make earth construction more reliable, durable, and accepted in modern building practices, while also facilitating the rehabilitation of ancient earth-based buildings [8].

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One of the most used mechanical characterisation tests is the compression test [9]; it can be used to measure strength, stiffness, deformation capacity and other mechanical parameters during construction. This parameter enables the design of structures capable of withstanding anticipated loads. A way for control offices to assess the quality of a project and monitor the performance of a RE construction is to verify the mechanical behaviour of the compacted soil through its main indicator: the compressive strength. For instance, Canivell et al. [10] proposed a quality control protocol to be applied before and during the construction of a RE wall, including compressive strength tests on samples.

To date, no new standardised test procedure has been established. Consequently, several experimental procedures exist for performing compressive strength tests and producing RE specimens [8,9]. In the literature, three main approaches can be identified for producing samples to be tested in an unconfined compression test.

The first involves wall-scale specimens, manufactured at a large scale to represent actual RE constructions such as walls, wallets, or prisms. The second approach concerns sample-scale production, where specimens are either extracted from existing structures (cored or sawed), which involves damaging the existing structure. The third approach is also related to sample-scale production, fabricated from raw materials with adjusted parameters to achieve smaller dimensions and higher quantities. In all cases, specimen fabrication requires considerable preparation time and often demands specific equipment or testing machines due to the large size of the specimens.

However, a wide variety of procedures are currently used to perform compression tests on RE, and many studies highlight the influence of various factors on the resulting compressive strength. The following section aims to present the main influencing factors.

First, specimen size is a major factor. Maniatidis and Walker [11] reported considerable variations in mechanical performance between small-scale cylinders, full-scale prisms, and columns made of the same material. Bui et al. [12] and Pelé-Peltier et al. [9] also investigated the multi-scale mechanical behaviour of RE and showed that compressive strength measured on smaller specimens was higher than that obtained on larger ones. This well-known scale effect strongly influences compressive strength, mainly because RE typically contains aggregates up to 10 cm in size or greater [13]. Consequently, reducing specimen size may require sieving the material, which alters the particle size distribution and, thus, the mechanical properties. To some extent, this also raises questions about the representativeness of the samples.

The specimen manufacturing process strongly affects the mechanical properties of the material. It includes several parameters, such as the compaction process (layer thickness, number of layers, compaction energy, and compaction method). The compaction process directly influences density variation within a RE layer and across the entire specimen, as studied by Rodríguez-Mariscal et al. [14]. For instance, Hall and Djerbib [15] used manual compaction tools derived from the standard Proctor test [16], while Jaquin et al. [17] used a vibrating hammer to produce their specimens. Other studies aimed to minimise these effects by producing homogeneous compacted earth samples representative of a specific location within the RE layer. For example, Champiré et al. [18] and Bui et al. [12] applied a double-compaction process in their work. In addition, several authors have reported the strong influence of conditioning moisture on the mechanical behaviour (strength and deformability) of RE, including Champiré et al. [18] and others [19, 20].

Another key parameter is the slenderness and geometry of the specimen. Both factors are related to the testing configuration and can significantly affect results, particularly through frictional effects. Venkatarama Reddy and Prasanna Kumar [21] reported that the compressive strength of stabilised RE decreased by almost 30% as the aspect ratio increased from 4.65 to 19.74. Ciancio and Gibbings [22] further demonstrated that slenderness strongly influences the compressive strength of RE, with variations up to nearly a factor of two between specimens with ratios of 2 and 0.75. They also showed that the specimen's base geometry (cylindrical or prismatic) plays an important role in compression test results. Tripura and Das [23] confirmed these findings, demonstrating that the shape and size of specimens strongly affect strength, mechanical behaviour, and crack patterns, emphasising the need to consider geometry for a reliable interpretation of experimental results. Slenderness ratio of 2 is often adopted to limit friction effects, following conventional compression tests practices on materials such as concrete, where a 2:1 height-to-diameter ratio is standard [6]. Aubert et al. [24] highlighted the combined influence of aspect ratio and friction: a raw earth block with an aspect ratio of 0.35 reached a compressive strength exceeding 45 MPa, whereas the same material, tested in the same direction with an aspect ratio of 2, achieved only 5.5 MPa. To counter this effect, Ciancio and Gibbings [22] have already highlighted the promising nature of installing a Teflon anti-creep system on cement-stabilised soil samples. To date, this result has not been extended to unstabilised soil samples, which generally exhibit higher levels of lateral deformation (higher Poisson's ratio which can be higher than 0.35 when the water content increase [20]) and therefore potentially increased friction issues. Finally, it is now standard practice to test specimens with a slenderness ratio of 2 to limit the influence of frictional effects on compression test results (e.g., Kumar et al. [25]). However, high-slenderness RE specimen preparation is time-consuming. Slenderness 1 specimens also offer practical advantages: they are directly compatible with the standardised Proctor mould, inexpensive, widely available in laboratories and aligns with other practices, particularly in Germany, where cubic specimens (aspect ratio 1) are used for concrete and RE material [26, 27]. In summary, slenderness 2 represents the conventional approach to reduce friction effects, while slenderness 1 provides a practical alternative.

Through these examples, it can be seen that many parameters influence the compressive strength of RE. Miccoli et al. [28] and Avila et al. [29] have also collated literature results obtained for earth construction specimens, showing the wide dispersion of mechanical property values. The anti-friction system proposed by Ciancio and Gibbings [22], consisting of a Teflon plate, was applied to stabilised earthen samples with smooth surfaces. For unstabilised RE, surface roughness and material irregularities may hinder the effective implementation of this system.

The aim of this article is to provide a method for compression testing of RE samples. The addition of an anti-friction system during testing is proposed, enabling the production of specimens with a slenderness ratio of 1, contrary to what is usually done. This saves considerable time in the manufacture of RE specimens. A production method based on a small sample, which can be produced and tested in any laboratory where civil engineering research is conducted, is presented. To do so, the manufacturing process presented in this article is inspired by the standards [16] and [30], which are among the most widely used tests in road geotechnics and require minimal and low-cost equipment. In order to validate a test protocol for improving the production time of RE samples by adding an anti-friction system during testing, production parameters such as slenderness and surfacing method were varied.

2 Material and method

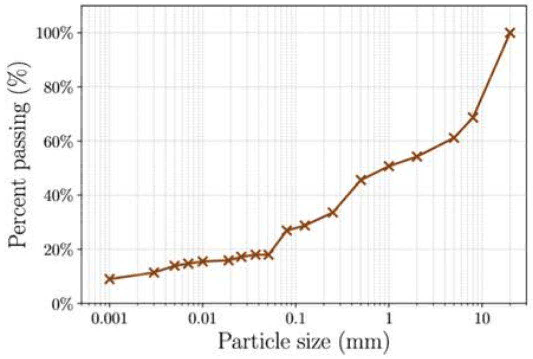
2.1 Earth identification

The earth investigated in this study comes from the Rhône-Alpes region in France and was used to build the structural RE walls of a school in Villefranche-sur-Saône, which opened in 2024. This confirms that the earth is suitable for actual construction.

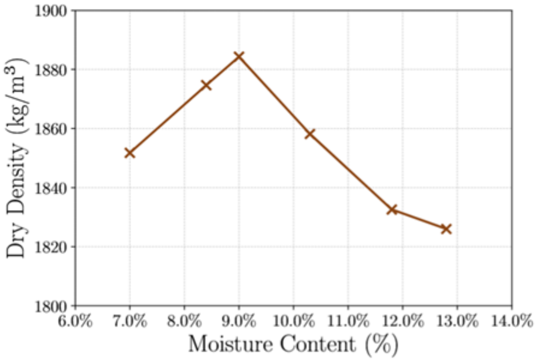
The determination of the grain size distribution was carried out in accordance with ISO 17892-4 [31]. The curve is shown in Figure 1a. The particle size analysis shows a composition dominated by the coarse fraction, with 45% gravel (> 2 mm). The sand fraction (2 mm to 0.08 mm) represents 27.29%, while the fine fractions are made up of 17.97% silt (0.08 mm to 0.002 mm) and 8.99% clay (< 0.002 mm).

A compaction curve, similar to the Proctor one, but considering a compaction energy of 1670 kJ/m^3 was produced (Figure 1b). This compaction energy was chosen to achieve an optimal dry density in the samples, similar to that obtained in the Villefranche-sur-Saône School's RE walls. The maximum dry density is reached at a water content of 9% and its value is 1884 kg/m^3. This density corresponds to the range of 1700-2000 kg/m^3 reported for RE in the construction field [31].

The earth was sieved to 20 mm and moistened to achieve a water content of 9%. The earth-water mixture was prepared by hand, then hermetically sealed and set aside for 24 hours to ensure homogeneity of water content. The specimens were manually compacted in layers of 38 mm, in 8 sequences of 7 blows per layer using the modified Proctor hammer. This corresponds to a compaction energy of 1.67 MJ/m^3. After fabrication, the samples were left in ambient air for one week, then placed in an oven at 65°C until their mass had stabilised in accordance with ISO 12570/A1 [33]. This method ensures a homogeneous water content in the sample without significantly altering the material, particularly the clays, and allows a repeatable drying process in any laboratory. The final water content of the samples was determined immediately after testing in accordance with ISO 17892-1 [34] at 105°C.



(a) Grain size distribution



(b) Modified Proctor

Figure 1. Analysis curves of the earth studied.

A total of 31 specimens were manufactured, with variations in the following parameters: surfacing technique, slenderness ratio, and testing conditions; with or without the anti-friction system (Table 1).

Two slenderness ratios were compared. Slenderness ratio of 1, denoted "1", corresponds to samples with a diameter equal to their height (Ø = 152 mm, h = 152 mm) and produced in four layers, while slenderness ratio of 2, denoted "2", corresponds to samples twice as tall (Ø = 152 mm, h = 304 mm) and comprising eight layers.

After compaction specimens exhibited hollows and hard spots on their upper surfaces, as illustrated in Figure 3a, implying an improper surface for applying a homogeneous distribution of compressive stress. Two finishing methods were tested: the first involved moistening soil sieved to 3 mm, then trowelling it with a levelling ruler, as illustrated in Figure 2a and captioned by the letter "r" in Table 1, with the resulting surface shown in Figure 3b. The second method involved sanding the surface and pebbles with a diamond disc, as shown in Figure 2b, with the resulting surface shown in Figure 3c and captioned by the letter "s" in Table 1.

Of the 31 samples, the number of samples per parameter is: 5 x 1r, 8 x 1r*, 2 x 1s*, 6 x 2r, 8 x 2r*, 2 x 2s*. The asterisk "*" refers to the specimens tested with the anti-friction system described in Section 2.3.

(a) Levelling off a thin earth layer with a straightedge

(b) Surface sanding using a power sander

Figure 2. Methodology for obtaining a clean and parallel surface.

Table 1. Designation of the 31 samples according to the studied parameters.

	Parameters	Denomination
Slenderness	1: Ø = 152 mm, h = 152 mm 2: Ø = 152 mm, h = 304 mm	1 2
Surfacing method	Ruler Sanding	r s
Anti-friction system	With Without	*

(a) Without surfacing

(b) Ruler

(c) Sanding

Figure 3. Photos of upper surfaces.

2.2 Compression test protocol

Compression tests were carried out on the Zwick-Roell electromagnetic press at the 3SR laboratory. Tests were displacement-controlled at a speed of 1.2 mm/min after a preload of 1 kN and were stopped once the applied force had dropped by 10% from the peak load. Some specimens were tested without any device at the specimen/press interface, while others were tested with an anti-friction system, positioned at both interfaces between the RE sample and the press. Figure 4 illustrates the configuration and components of the system.

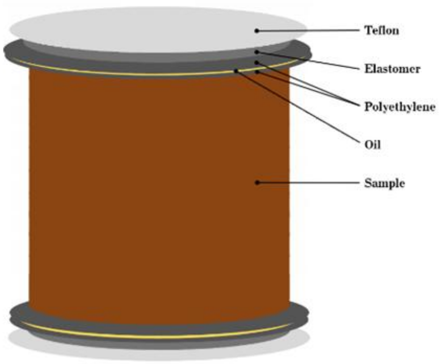


Figure 4. Symmetrical anti-friction system.

The anti-friction system is composed of several layers. First, a 2 mm thick Teflon sheet was placed at the interface between the loading platen and the elastomer layer. Its role was to provide a smooth, regular contact surface while maintaining a slight confining effect, thereby reducing stress concentrations at the contact with the specimen. Beneath it, a 3 mm elastomer layer made of Nitrile Butadiene Rubber (NBR), a butadiene-acrylonitrile copolymer, was introduced. This material was selected for its elastic deformability higher than those of the sample and ability to redistribute stresses, thus ensuring homogeneous load transfer across the specimen despite local surface roughness. Finally, a double oiled polyethylene film was placed in direct contact with the specimen. This consisted of one polyethylene sheet lightly oiled and covered by a second sheet, forming a sliding interface. This system limits the lateral confinement that could otherwise be induced by the elastomer during loading, and thereby approximating uniaxial compression conditions as closely as possible.

3 Experimental results

Figure 5 presents the average values of compressive strength obtained for different experimental groups, accompanied by error bars representing the standard deviation. Table 2 summarises the main results; the mean values of the maximum stress (denoted $\bar{\sigma}$ in MPa), the average water content of the samples immediately after testing (denoted $\bar{w}_{test,105}$ in %) and the average density of the samples (denoted $\bar{\rho}$ in kg/m³), determined by weighing and measuring the samples just before the test, along with the standard deviations (std).

Regarding the mean test densities the values are consistent across all sample groups, ranging from 2034 kg/m³ (1r*) to 2079 kg/m³ (2s*), with a total spread of only 45 kg/m³. This narrow range indicates good control over compaction quality. Standard deviations are also low (between 9.4 kg/m³ and 27 kg/m³ depending on the sample group), confirming the repeatability and reliability of the sample preparation process.

However, according to Bui et al. [12], the variation in compressive strength remains limited (approximately 10% for clayey soils) for moisture contents below a 4% threshold. Based on the sensitivity reported by Araldi et al. [36]-estimated at a 12-15% strength loss per 1% increase in moisture-the maximum variation of 0.7% observed in the present study should theoretically result in a strength reduction of only 8-11%. Given that the experimentally observed difference reaches approximately 50%, it can be concluded that such a significant variation cannot be reasonably attributed to moisture content alone.

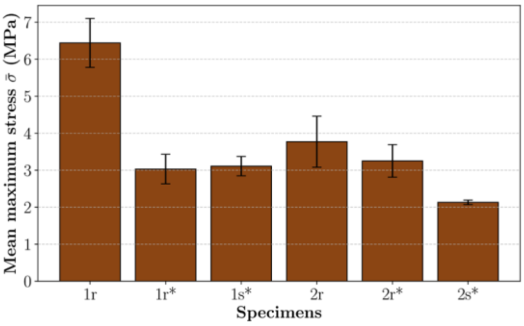


Figure 5. Average of the maximum stress.

Table 2. Summary of mean mechanical and physical properties.

Name	$\bar{\sigma}$ (MPa)	std ($\bar{\sigma}$)	$\bar{w}_{test,105}$ (%)	std ($\bar{w}_{test,105}$)	$\bar{\rho}$ (kg/m³)	std ($\bar{\rho}$)
1r	6.44	0.66	0.49	0.03	2050	9.4
2r*	3.03	0.40	0.46	0.25	2034	18.5
1s*	3.11	0.26	0.31	0.24	2056	11.2
2r	3.77	0.69	0.36	0.06	2064	15.8
2r*	3.25	0.44	0.37	0.13	2058	14.8
2s*	2.13	0.06	1.07	0.02	2079	27.0

3.1 Influence of slenderness

To assess the influence of slenderness, comparisons were made between specimens tested without any anti-friction system: 2r (slenderness 2) and 1r (slenderness 1). The results show that 1r exhibits a significantly higher average strength (6.44 MPa) compared to 2r (3.77 MPa), suggesting that a lower slenderness ratio leads to a stronger response under the same conditions. These results are in agreement with the literature and highlight the role of the frictional effect between the press and the specimen. Moreover, the standard deviations are very close (0.66 MPa for 1r and 0.69 MPa for 2r), showing that both series of results are equally reliable.

3.2 Higher performance materials

For specimens with slenderness 1 without the anti-friction system (1r), the average maximum stress reached 6.44 MPa with a standard deviation of 0.66 MPa. In contrast, specimens equipped with the anti-friction system, 1r* and 1s*, exhibited significantly lower average stresses of 3.03 MPa (std: 0.40 MPa) and 3.11 MPa (std: 0.25 MPa), respectively. These values are approximately half those observed without the system and are closely aligned with the results obtained for slenderness 2 specimens, highlighting the effectiveness of the anti-friction system.

For the specimens tested using the anti-friction system (Figure 6a), clear vertical cracks were observed all along the samples. Although this is not undeniable proof this type of cracking pattern may indicate homogeneous deformation and stress conditions within the samples, and therefore a less pronounced effect of fretting at the interface with the press. In contrast, specimens tested without the anti-friction system (Figure 6b) exhibited a markedly different crack pattern, with the faces in contact with the metallic platen remaining uncracked. Crack propagation appeared more irregular and heterogeneous near the specimen extremities, indicating local stress redistribution and confinement induced by friction at the interfaces. However, identifying a well-defined failure cone, typically associated with frictional confinement in compression tests, remains difficult, as it develops within the interior of the specimen and cannot be directly observed.

(a) With the anti-friction system

(b) Without the anti-friction system

Figure 6. Crack patterns.

It is also noteworthy that visible signs of friction were observed on slenderness 2 specimens without the anti-friction system (2r), which recorded an average maximum stress of 3.77 MPa with a standard deviation of 0.69 MPa. Meanwhile, their counterparts with the system (2r*) reached a slightly lower mean value of 3.22 MPa (std: 0.44 MPa). The observed friction effect on slenderness 2 specimens may be attributed to the friction coefficient of RE.

3.3 Influence of surfacing method

Compressive strength results show similar performance between samples surfaced with a ruler (1r*, 3.03 MPa) and those sanded (1s*, 3.11 MPa), with comparable standard deviations of 0.36 MPa and 0.26 MPa. For samples with a slenderness ratio of 2, 2r* and 2s* exhibit strengths of 3.25 MPa (std: 0.44 MPa) and 2.13 MPa (std: 0.06 MPa), respectively. This strength variation is more attributable to moisture content than to the surfacing method and remains consistent.

The two surfacing methods do not appear to significantly affect compressive strength, suggesting that both techniques produce surfaces that are sufficiently flat and consistent for accurate testing. Considering the consistent results across surfacing techniques and practical aspects, ruler surfacing is recommended for practical applications, as it requires fewer tools, generates no dust, and is less time-consuming than sanding.

4 Discussion and conclusion

This study introduces a procedure for unconfined compression testing applied to RE specimens. Combined with a fabrication protocol for low-slenderness samples, the testing procedure incorporates an anti-friction system. This system minimises the frictional interface effects. The effect of slenderness and frictional test conditions on the compressive strength results of a set of RE samples was investigated.

For all tested configurations, the low dispersion of results demonstrates the high repeatability of the tests. In terms of specimen preparation, the dry density proved to be highly consistent, while in testing, the compressive strength exhibited very low standard deviations.

The results highlight the significant influence of both slenderness ratio and the presence of the anti-friction system on compressive strength, underscoring the need to control these aspects to ensure consistent and reliable data. The results obtained on specimens with a slenderness ratio of 2 and those with a ratio of 1 using the anti-friction system are found to be comparable. Based on these findings, it is concluded that the proposed system provides a simplified and reproducible laboratory testing protocol.

As the apparent compressive strength measured in this study on low-slenderness specimens can be closely related to the material's unconfined compressive strength measured on specimens with a slenderness ratio of 2, it allows the use of slenderness 1 specimens while yielding results comparable to those obtained with slenderness 2. This approach reduces the required material, time, and energy for specimen preparation by approximately 50%.

The setup may also present limitations for stiffness determination. As the anti-friction system deforms with the specimen, relying only on platen displacement leads to an inaccurate elastic response. Furthermore, for small slenderness, the installation of extensometers can be more challenging than on samples with a slenderness of two. Although extensometers are routinely used in some laboratories, this study does not aim at elastic modulus determination, and therefore this limitation does not affect the main conclusions.

Overall, the full protocol (specimen fabrication and anti-friction system) provides a solid basis for the characterisation of RE materials. It supports both the technical and comparative assessment of these materials for construction purposes and promotes their broader adoption in sustainable construction.

Future work should explore the applicability of the proposed system and/or its possible adaptation (thickness of the elastomer, elastic characteristics of the elastomer and polyethylene, type of lubricants, etc.) to a wider range of soils and testing conditions. For RE, the complete protocol (combining specimen fabrication and the anti-friction system) remains particularly relevant, as sample preparation strongly influences test outcomes. However, extending its use to materials with higher water contents, which may interact differently with the anti-friction system, should be further investigated. Similarly, testing specimens with higher moisture levels would help define the method's limitations and refine its scope of applicability.

The potential application of the anti-friction system to pre-formed elements, such as earth bricks tested according to NF EN 772-1 [35], should also be considered. In this case, only the surface treatment and anti-friction aspects of the protocol would apply, since fabrication is already standardised. For instance, some earthen bricks exhibit unusually high compressive strengths [8], largely due to confinement effects; in such cases, the anti-friction system could help eliminate these parasitic effects during testing.

Authorship statement (CRediT)

Claire Durhône: Conceptualisation; Methodology; Investigation; Writing – Original Draft. **Marie-Sarah Force:** Conceptualisation; Investigation; Writing – Original Draft. **Florent Vieux-Champagne:** Conceptualisation; Supervision; Validation. **Antonin Fabbri:** Supervision; Validation.

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