



Tropical earthen plastering mortars: Effects of earth mineralogy, earth-to-sand proportion, and moisture conditioning

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ABSTRACT

This study investigates the physical and mechanical behaviour of tropical earthen mortars, focusing on the influence of clay content, mineralogy and moisture condition. To address the limited documentation on tropical earthen mortars, eleven mortars were produced using three tropical earth and three proportions of added sand. Two of the earth were of pedogenetic origin, whereas the third was derived from gneiss aggregate washing residue. The added sand consisted of crushed basalt fines generated during gravel production. Materials were characterised by particle-size distribution and mineralogical composition, and the mortars were evaluated for porosity, bulk density, shrinkage, flexural (FStr) and compressive (CStr) strengths. Moisture sensitivity was assessed under high-humidity conditioning through the degree of saturation at mechanical failure. The results show that clay content and mineralogical characteristics strongly influenced water demand, shrinkage, porosity and density. Porosity ranged from 30% to 48%, with higher values in clay-richer mortars. Sand addition substantially reduced shrinkage, reaching up to 79% in the most clay-rich mixtures. FStr ranged from 0.6 to 1.0 MPa, while CStr ranged from 0.5 to 1.0 MPa, with several formulations exceeding the minimum requirement of EN 998-1. Moisture had a marked effect on performance, with CStr generally decreasing more sharply than FStr as saturation increased. Overall, the results demonstrate that clay content, mineralogy and moisture state play a decisive role in the behaviour of low-embodied-energy tropical earthen mortars, supporting their wider application as building plasters.

1. Introduction

In recent years, the interest in earthen construction products has increased due to the search for low-carbon building solutions, circular use of resources, and healthier indoor environments [1]. Among these products, earthen mortars are attractive because of their low embodied energy, vapour permeability, and hygroscopic buffering capacity [2–7]. However, the broader use of unstabilised

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earthen mortars is still limited by concerns regarding durability and moisture sensitivity, particularly when no chemical stabilisers are used [8].

Earthen mortars are typically composed of a clay-rich earth acting as binder and an additional granular fraction that contributes to dimensional stability and packing. In practice, sandy correction is often required to reduce shrinkage and improve overall performance

Table 1

Literature synthesis of earthen mortars studied and test results.

Study source	Mortars analysed	Results
Delinière et al. [27]	E:S 1:2.0–1:2.4; Cc: 6–11%; R: France; M: montmorillonite, chlorite, illite, kaolinite; W: 17–21%.	WBD: 2.00–2.10 g/cm ³ DBD: 1.70–1.80 g/cm ³ LS: 1.5–2.5% FStr ^a : 0.5–0.7 MPa CStr: 1.3–2.1 MPa
Gomes et al. [24]	E:S 1:0–1:3.8; Cc: 10–19%; R: Portugal; M: mica, illite, kaolinite, chlorite.	WBD: 1.87–2.00 g/cm ³ DBD: 1.66–1.91 g/cm ³ P: 25–35% LS: 0–1.2% FStr ^a : 0.2–0.4 MPa CStr: 0.5–1.0 MPa
Santos et al. [5]	E:S 1:4.82; Cc: 8%; R: Portugal; M: kaolinite/illite; W: 10%.	WBD: 1.56 g/cm ³ DBD: 1.77 g/cm ³ LS: 0.1% FStr ^b : 0.2 MPa CStr: 1.0 MPa
Santos et al. [30]	E:S 1:3.08; R: Portugal; M: illite; W: 17–20%.	WBD: 2.00–2.06 g/cm ³ DBD: 1.77–1.79 g/cm ³ LS: 0–4% FStr ^b : 0.2 MPa CStr: 0.4–0.6 MPa
Lagouin et al. [15]	E:S 1:1–1:4; Cc: 1.5–17%; R: France; M: illite, chlorite, vermiculite, montmorillonite, kaolinite; W: 18–45%.	VS: 2.5–22% FStr ^a : 0.2–0.9 MPa CStr: 0.5–2.4 MPa
Santos et al. [2]	E:S 1:4.8; R: Portugal; M: illite, kaolinite, microcline, montmorillonite; W: 21%.	WBD: 1.97 g/cm ³ DBD: 1.72 g/cm ³ LS: 0.7% FStr ^c : 0.5 MPa CStr: 1.8 MPa
Randazzo et al. [31] Pachamama et al. [17]	Cc: 9–31%; R: Italy; W: 20–25%. E:S 1:1.57–1:3.96; Cc: 5–14%; R: Portugal and Brazil; M: illite, kaolinite, goethite; W: 20–22%.	P: 25–34% WBD: 1.40–1.85 g/cm ³ DBD: 1.57–1.70 g/cm ³ LS: 0.4–2.0% FStr ^d : 0.4–0.7 MPa CStr: 0.7–1.4 MPa
Hamard et al. [32] Gonzalez-Calderon et al. [13]	Cc: 3–18%; R: France. Cc: 13%; W: 25%.	LS: 4–17% DBD: 1.74 g/cm ³ P: 29.6% FStr ^a : 0.6 MPa CStr: 2.4 MPa
McGregor et al. [3]	E:S 1:1–1:4.89; Cc: 4–17%; R: France; W: 14–22%.	DBD: 1.60–1.83 g/cm ³ P: 18–32%
Parracha et al. [33]	M: illite, kaolinite, hematite; R: Portugal; W: 25%.	WBD: 2.00 g/cm ³ DBD: 1.69 g/cm ³ P: 29.8% FStr ^e : 0.3 MPa CStr: 0.7 MPa
Lima et al. [34]	E:S 1:3.63–1:12.2–1:4.46; R: Portugal; M: illite, kaolinite, hematite, montmorillonite; W: 13–21%.	WBD: 1.96–2.13 g/cm ³ DBD: 1.74–1.91 g/cm ³ P: 25–34% LS: 0.4–3.3% FStr ^a : 0.2–0.3 MPa CStr: 0.5–0.9 MPa

Notation: E:S – Earth to Sand mass ratio (wt); Cc - Clay content; R - Earth origin country; M – Fine fraction minerals; W - Water content; WBD - Wet bulk density; DBD - Dry bulk density; LS - Linear shrinkage; VS - Volumetric shrinkage; P - Porosity; FStr - Flexural strength; CStr - Compressive Strength; Conditioning - ^a 23 ± 2 °C and 50 ± 5% RH, ^b 20 ± 2 °C and 65 ± 5% RH, ^c 21 ± 5 °C and 65 ± 2% RH, ^d 26 ± 3 °C and 63 ± 5% RH, ^e 18 ± 2 °C and RH 46 ± 5%.

[9–14]. Although recent research has frequently focused on stabilised formulations containing lime, cement, or alkali-based binders [2,15–18], such additions increase embodied energy and reduce reversibility and moisture buffering of the mortars, thereby partially offsetting the environmental advantages of earth-based products [5]. For this reason, a better understanding of the behaviour of unstabilised earthen mortars remains essential, especially under variable moisture conditions.

A major limitation in the current literature is that most available datasets are based on earth from temperate regions and mild climates, whereas tropical earth remain comparatively underexplored [8,17,19]. This is relevant because tropical earth commonly present distinct pedogenetic and mineralogical features, including higher proportions of kaolinite, iron oxides, and gibbsite [20–22], which may affect shrinkage, porosity, and mechanical behaviour. Therefore, performance trends established for temperate-region materials cannot be directly assumed for mortars produced from tropical earth.

A further challenge lies in the mismatch between empirical data and existing normative frameworks. Standards such as DIN 18947 [23] were largely developed from temperate-region materials tested under moderate laboratory environments, typically around 20–23 °C and 50–65% relative humidity. Such conditions are useful for standardisation, but they do not represent the humid exposure regimes frequently encountered in tropical climates. As a result, the behaviour of unstabilised earthen mortars under high relative humidity and increasing moisture content is still insufficiently documented.

A review of recent studies also shows that shrinkage and strength are not yet addressed in a sufficiently integrated way. Linear shrinkage (LS) is commonly reported, whereas volumetric shrinkage (VS) is much less frequently included [8,15,24,25], despite its relevance for cracking risk and dimensional stability [24,26,27]. Likewise, mechanical performance is generally assessed after conditioning under moderate laboratory climates, with limited attention to how strength changes with increasing moisture or degree of saturation. From the perspective of unsaturated soil mechanics, this is a critical gap, since capillary forces and suction-related effects contribute to apparent cohesion and stiffness in earthen materials, but these contributions decrease as saturation rises [28,29].

A compilation of recent studies on earthen mortars is presented in Table 1 and results will be useful for comparison with the ones of the present study later on. Overall, previous work reveals wide variability in composition and performance, with clay contents ranging from 1.5% to 31%, earth:sand mass proportions (wt) from 1:0 to 1:12.2, and reported values of porosity from 18% to 35%, linear shrinkage up to 17%, volumetric shrinkage from 2.5% to 22%, flexural strength from 0.2 to 0.9 MPa, and compressive strength from 0.4 to 2.4 MPa.

Accordingly, and as mentioned before, the literature still shows important gaps, particularly the limited availability of datasets for unstabilised earthen mortars made from tropical earth, the scarce inclusion of volumetric shrinkage alongside linear shrinkage, and the still limited understanding of flexural and compressive strength as a function of saturation state under high-relative-humidity conditioning.

This study addresses these gaps by investigating unstabilised plastering mortars produced from three tropical earth with different clay contents and mineralogical compositions, combined with different complementary sand correction. Comparing between the earth properties and materials proportions, the specific objectives are: (i) to characterize the fresh-state, physical, and mineralogical properties of these mortars; (ii) to assess their dry bulk density, porosity, linear shrinkage, and volumetric shrinkage; and (iii) to evaluate flexural and compressive strength under different moisture/saturation states, including high-relative-humidity conditioning. By integrating tropical-material datasets with shrinkage and hygro-mechanical analysis within a single framework, the study seeks to improve understanding of how clay fraction, mineralogical assemblage, sand correction, and moisture condition may influence the performance of unstabilised plastering mortars. In this way, it aims to support more context-sensitive material selection and performance assessment for unstabilised earthen mortars intended for humid or seasonally wet tropical conditions.

By combining tropical-material datasets with shrinkage and hygro-mechanical analysis in a single framework, this study contributes not only to a more context-sensitive understanding of unstabilised earthen mortars for humid climates, but also to a broader interpretation of how clay fraction, mineralogical assemblage, sand correction, and moisture condition interact to control plastering mortars performance. In this sense, the results provide transferable criteria for material selection, sand correction, and moisture-sensitive performance assessment of unstabilised earthen mortars in other tropical regions where locally available earth are used under humid or seasonally wet exposure conditions.

2. Materials and methods

2.1. Materials

For the formulation of the mortars, three Brazilian earth of distinct origins were employed, designated as Lv, Bh and Rm, together with a crushed basaltic sand used for granulometric correction of the mortars. Lv and Bh correspond to excavated soils formed through pedogenetic processes [35], whereas Rm consists of a fine residue derived from the washing of gneiss aggregates for construction. In this study, these three materials are hereafter referred to simply as earth. Lv was collected in Apucarana, Paraná State, and corresponds to a Red Latosol, a widespread pedological class in Brazil [36]. Bh was obtained from foundation excavations and earthmoving works in the Metropolitan Region of Belo Horizonte, Minas Gerais State, without a precise pedogenetic classification. Rm was collected from settling ponds of a quarry in Minas Gerais, where fine particles generated during the washing of gneiss aggregates are deposited [37].

The aggregate employed was a by-product of basalt rock crushing for construction, supplied by a quarry in northern Paraná, Brazil. The fraction commercially classified as sand was used in its raw state and sieved into five size ranges (2.36–1.18 mm; 1.18–0.60 mm; 0.60–0.30 mm; 0.30–0.15 mm; 0.15–0.075 mm). In comparison, the remaining fractions were washed through a 0.075 mm sieve to remove fines and subsequently recombined to establish the grading curve adopted in the mortar formulations. Fig. 1 shows the geographical origin of the raw materials and the visual appearance of the collected earth samples.

2.2. Characterization of materials

The raw materials (Lv, Bh, Rm and sand) were characterised in terms of particle size distribution, density, mineralogical composition and thermal behaviour. Particle size distribution was determined by sedimentation and sieving according to NBR 7181 [38]. Particle density was measured according to NBR 17212 [39], and loose bulk density according to NBR 16972 [40].

Mineralogical composition was determined by X-ray diffraction (XRD) using an AERIS Malvern Panalytical diffractometer operating at 40 kV and 15 mA, with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). For each material, a representative portion of the fine fraction passing the 0.30 mm sieve was ground in a mortar and pestle until the entire sample passed through a 106 μm sieve. Diffractograms were recorded in the range of 4–70° 2 θ , with a step size of 0.02°/s. The diffractograms were analysed according to an internal procedure based on LNEC E 403 [41], using HighScore Plus software for peak identification and semiquantitative analysis by the Rietveld method. The structural models used in the refinement were obtained from the Crystallography Open Database [42–49].

Thermogravimetric and differential thermal analyses (TGA/DTA), together with derivative thermogravimetry (DTG), were carried out using a SETARAM TGA92 simultaneous thermal analyser. The samples were placed in a Pt–Rh crucible and heated from room temperature to 1000 °C at 10 °C min^{−1} under argon atmosphere (3 L h^{−1}).

2.3. Mortars and samples

2.3.1. Mortars formulation and fresh state characterization

In this study, 11 mortar formulations were prepared. For each earth, a reference mortar without sand addition was produced. Grading corrections were then applied at mass ratios of 1:1, 1:2, and 1:3 for the more clay-rich earth (Lv and Bh), and at 1:1 and 1:2 for the Rm earth. The 1:3 mix was not considered for Rm due to its inherently low clay content. Table 2 presents the mass and volumetric proportions of these mortars. The addition of −1, −2, −3 refers to the sand-added proportions.

Two experimental sets were carried out. The first set involved the evaluation of linear shrinkage (LS) in circular specimens, volumetric shrinkage (VS) in cubic specimens, and the determination of total open porosity. The second set was used to assess the mechanical parameters of newly cast mortars. Differences in water content between sets 1 and 2 for the same mortars, as shown in Table 2, are justified by the consistence adjustment ($175 \pm 5 \text{ mm}$), which was adopted as the control in the mortar production process. Based on the preliminary shrinkage results, which will be detailed in Section 3.4, the mechanical characterization of the reference mixtures Lv-Ref, Bh-Ref, and Rm-Ref was not performed in Set 2.

The mortars were prepared in a mechanical mixer following a standardised procedure. The dry materials were first weighed and placed into the mixer. Afterwards, water (in percentage to the total solids) was gradually incorporated over 30 s to initiate mixing. The process lasted a total of 9 min and comprised four stages: (i) mechanical mixing at low speed for 1 min 30 s; (ii) manual mixing with a plastic spatula for 2 min to break down agglomerates; (iii) resting period of 5 min; and (iv) additional mechanical mixing at low speed for 30 s. The water content was adjusted to ensure adequate workability, assessed by flow table consistence, determined according to NBR 7215 [50]. A target spread of $175 \pm 5 \text{ mm}$ was adopted, in line with DIN 18947 [23]. This range is recognised as the standard consistence for mortars, being associated with favourable mechanical performance and positive perception by workers during application [51]. However, it should be noted that the flow table specified in the Brazilian standard NBR 7215 [50] differs in dimensions and weight from that prescribed in the European standard EN 1015-3 [52]. Moreover, the volume of the truncated-cone specimen and the number of drops also vary, resulting in different energy inputs to the tested mortars. Assuming that energy dissipation in the flow table test arises from the viscoplastic deformation of the sample [53], the potential gravitational energy released at

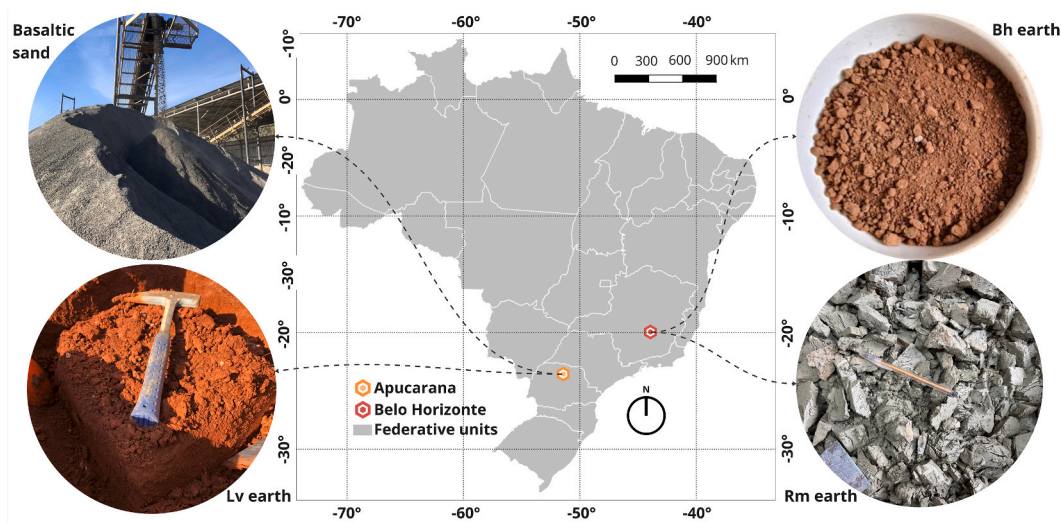


Fig. 1. Location of the raw material collection sites in Brazil and visual appearance of the materials used in the study.

Table 2

Mortars mass and volumetric proportions of earth and sand, and water content as a percentage of total mass in sets 1 and 2.

Mortar	Mass proportion		Volumetric proportion		Water (%)	
	Earth	Sand	Earth	Sand	Set 1	Set 2
Lv-Ref	1	-	1	-	59.6 ± 0.2	-
Lv-1	1	1	1	0.71	35.7 ± 0.4	34.6 ± 0.3
Lv-2	1	2	1	1.42	31.3 ± 0.2	28.9 ± 0.4
Lv-3	1	3	1	2.13	29.7 ± 0.3	27.1 ± 0.3
Bh-Ref	1	-	1	-	56.1 ± 0.5	-
Bh-1	1	1	1	0.57	34.8 ± 0.4	33.7 ± 0.4
Bh-2	1	2	1	1.14	28.4 ± 0.1	28.0 ± 0.2
Bh-3	1	3	1	1.72	26.0 ± 0.4	25.3 ± 0.2
Rm-Ref	1	-	1	-	49.2 ± 0.1	-
Rm-1	1	1	1	0.50	25.4 ± 0.2	25.2 ± 0.2
Rm-2	1	2	1	1.00	20.3 ± 0.5	20.2 ± 0.2

each drop can be used to estimate the equivalent work. Based on this approach, it was calculated that approximately eight drops with the Brazilian equipment are required to match the energy dissipated in the EN 1015-3 [52] procedure, thereby achieving the consistence limit established by DIN 18947 [23].

The wet bulk density was determined according to NBR 13278 [54], and the moisture content was measured immediately after mixing of the mortar, using the oven-drying method as specified in NBR 6457 [55].

Additionally, to better capture the relationship between mortar water content and consistence, and to enable comparisons with other compositional and fresh-state parameters, such as clay content and wet density, the Fluidity Index (FI) was adopted. In the present study, FI is defined as the ratio of the measured consistence (flow-table spread, in millimetres) to the mortar's water content. The FI can be interpreted as the spread diameter, in millimetres, corresponding to a 1% increase in the water content. For instance, a FI of 500 indicates that, for every 1% increase in water content, the spread diameter increases by 5 mm. Accordingly, higher FI values indicate greater apparent fluidity for a given amount of mixing water. It should be noted, however, that FI is used here as an empirical, study-specific descriptor of water-normalised spread, intended exclusively for comparative purposes within the present experimental programme. Therefore, it should not be construed as a standardised rheological parameter, nor confused with the flow index of the Herschel–Bulkley model or with fundamental rheological descriptors such as yield stress or plastic viscosity.

2.3.2. Mortar specimens

The specimens were prepared in different geometries and conditioning according to the requirements of each test. As detailed in Table 3, the different specimen geometries were not only defined by the requirements of each test, but also involved distinct moulding and compaction procedures. Therefore, differences observed between specimen types, especially for density-, porosity- and shrinkage-related results, should be interpreted considering that specimen geometry and moulding/compaction procedure were not independent variables in the experimental programme. Table 3 presents the specimen dimensions, preparation procedures, conditioning and number of samples, while Fig. 2 illustrates the five specimen types employed.

Two conditioning regimes were employed: (i) 14 days in a closed environment, protected from direct solar radiation (25 ± 1 °C and relative humidity of $66 \pm 11\%$, set 1); and (ii) 14 days, consisting of the first 7 days under laboratory conditions protected from direct solar radiation, followed by 7 days in a humid chamber (21 ± 2 °C, relative humidity >95%, set 2). The latter condition was adopted to simulate typical conditions of humid bioclimatic zones, which are widely found across the Brazilian territory, to assess how critical a

Table 3

Details of specimens, preparation, testing, and packing.

Type	Dimensions (mm)	Number per type of test for each mortar						Preparation
		DBD	NGP	LS	VS	FStr	CStr	
Cylindrical ^a	30 × 40 (height × diameter)	3	3					Cut from the cubic specimens.
Rectangular ^a	50 × 30 × 15	3	3					Cut from circular specimens.
Prismatic ^b	160 × 40 × 40	4		4		4	4	Manually moulded and compacted in two layers with 20 manual strokes per layer, followed by manual surface levelling.
Cubic ^a	40 × 40 × 40			3	3			Manually cast in two layers, each compacted with 10 manual strokes using a metallic spatula; after the second layer, the surface was levelled, the specimen was placed on the flow table and subjected to eight rotations to homogenise the mortar and release entrapped air; additional mortar was added to compensate for settlement, followed by final levelling.
Circular ^b	145 × 15 (diameter × thickness)			3				Manually cast in a single layer, spread and levelled; three drops of approximately 1 cm were applied to release entrapped air, followed by refilling and re-levelling when necessary.

Note: DBD – Dry bulk density; NPG – nitrogen gas porosimetry; LS – linear shrinkage; VS – volumetric shrinkage; FStr, CStr – flexural and compressive strengths; Conditioning: ^a 14 days in a closed environment; ^b last 7 days in a humid chamber.

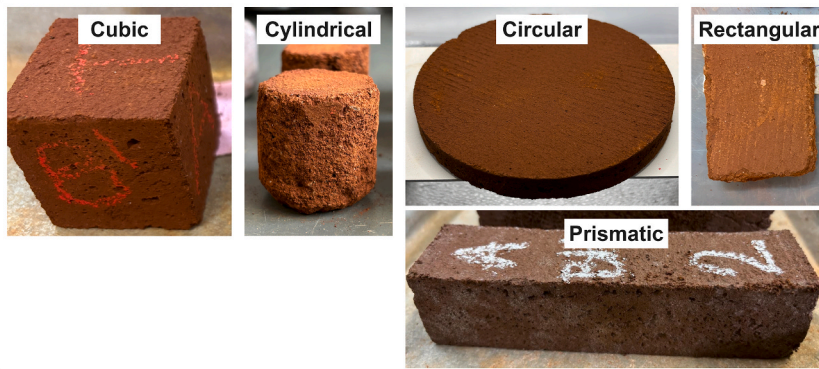


Fig. 2. Specimen geometries used in the experimental program: cylindrical cut from the cubic; rectangular cut from the circular.

scenario it can represent for earth-based construction composites. These earthen composites are susceptible to the presence of moisture due to the hydrophilic nature of clay particles. Under such conditions, the strength of the mechanical bonds between clay particles and mineral grains (such as sand) can be reduced, eventually compromising the internal cohesion, stiffness, and load-bearing capacity of the composite [56,57].

2.4. Mortars hardened state test methods

Total open porosity (P), defined as the percentage ratio between the difference of the apparent volume (V_A) and the real volume (V_R) relative to the apparent volume: $P (\%) = 100 \cdot (V_A - V_R) / V_A$. V_R was determined using a gas pycnometer ACP (model AD 200), with nitrogen gas as the working fluid. Gas pycnometry is a reliable method for measuring the volume of porous materials based on the Boyle–Mariotte law, and further details on the procedure can be found in Tamari [58]. V_A in turn, was obtained through the paraffin clod method, adapted in accordance with NBR 16867 [59]. This procedure was performed for both cylindrical and rectangular specimens. The use of both geometries is justified by the fact that their moulding processes differ, which can influence the porosity of the specimens and, consequently, their physical properties. The rectangular samples were cut from circular specimens, which simulate the manual application of the mortars, closely resembling on-site coating practices. In contrast, the cylindrical samples were cut from cubic specimens that were compacted with higher energy to ensure sample homogeneity, following procedures commonly adopted in laboratory conditions. The repeatability of the technique was investigated by conducting three independent analyses on the same sample.

The dry bulk density of mortars was determined on cylindrical, rectangular, and prismatic specimens based on the mass-to-volume ratio. For the cylindrical and rectangular specimens, bulk density was determined in accordance with NBR 16867 [59]. For the prismatic specimens, the procedure followed was in accordance with EN 1015-10 [60]. In all cases, testing was conducted with the specimens in their hygroscopic state, rather than after oven-drying at 105 °C, as specified in EN 1015-10 [60].

Linear drying shrinkage was measured on circular and prismatic specimens. For the linear shrinkage (LS) of circular specimens, dimensions were recorded at 1, 2, 7, and 14 days after casting. At 1 and 2 days, measurements were obtained through photographic image analysis following a standardised procedure, since the fresh state of the mortar at these ages prevented the use of a calliper without damaging the specimens. Moreover, because dimensional variations at early ages are minor, image analysis was considered more appropriate for detecting slight displacements while also providing a visual record of the mortars over time.

Fig. 3 shows the photographic setup used for image acquisition. The system consisted of a closed box with a circular LED light source mounted on the upper panel to provide uniform illumination (Fig. 3a), and a camera positioned vertically on the top cover (Fig. 3b), aligned with a central opening to ensure a constant focal distance and perpendicular imaging (Fig. 3c). The specimens were placed inside a PVC ring positioned on an MDF plate and levelled with a spirit level to guarantee stability during capture. Images were

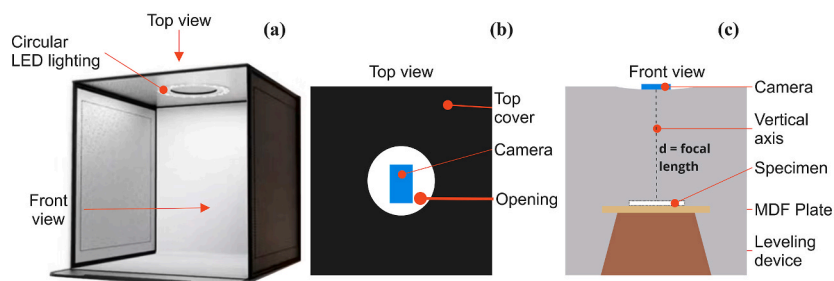


Fig. 3. Details of the photographic setup showing: (a) overview; (b) top view; (c) front view.

obtained using the main camera of a smartphone equipped with a 26 mm-equivalent lens, $f/1.6$ aperture, 48 MP sensor, and native resolution of 6048×8064 pixels.

At 7 and 14 days, complementary measurements were performed using a calliper (0.01 mm resolution) by recording four diametrical readings. LS was then determined as the relative change in specimen length over time, calculated from the difference between the initial length (measured immediately after moulding) and the length at a given age, normalised by the initial length.

Photographic image analysis was performed using ImageJ, an open-source software widely used for quantitative image processing. Specimen contours were manually delineated with segmented lines, and the enclosed area was first measured in pixels and then converted to metric units, enabling accurate determination of surface area at each age. LS of the prismatic specimens was qualitatively observed during demoulding and quantitatively determined in accordance with DIN 18947 [23], by comparing the specimen length with the corresponding mould length.

VS was assessed 14 days after casting by measuring specimen dimensions with a 0.01 mm-resolution caliper. For each cube, 16 measurements were taken, twelve on the lateral faces along the three orthogonal axes and four along the edges, to obtain mean directional dimensions and calculate specimen volume. Three specimens per mixture were tested, and volumetric shrinkage was expressed as the relative change between the measured and initial volumes.

The flexural strength was determined in accordance with EN 1015-11 [61] using a Shimadzu universal testing machine with a capacity of 300 kN, equipped with a 5 kN load cell and a loading rate of 5 N/s. Compressive strength was determined using the same equipment, under a controlled loading rate of 50 N/s, with a 5 kN load cell.

To assess post-failure moisture content, following the compressive strength test, the fractured parts of each specimen were immediately sealed in plastic bags to prevent evaporation. The moisture content after failure was then determined by the oven-drying method, at 100 ± 5 °C, until constant mass was achieved.

2.5. Statistical assessment

The statistical significance of the observed differences was assessed using Welch's *t*-test, which was selected because it does not assume homogeneity of variances and is appropriate for small sample sizes and unequal dispersions. Two comparisons were performed: (i) porosity between cubic and rectangular specimens and (ii) LS between 7 and 14 days. For each formulation, we report the difference between means (Δ mean), the *t* statistic, the degrees of freedom (df) adjusted using the Welch–Satterthwaite approximation, and the *p*-value, adopting a 5% significance level. Accordingly, $p < 0.05$ was interpreted as evidence of a statistically significant difference between the compared conditions, whereas $p \geq 0.05$ was interpreted as no statistical evidence of a difference under the evaluated conditions. For further details on the test's mathematical foundations, *p*-value computation, and limitations related to multiple comparisons, the reader is referred to García-Pérez [62].

3. Results and discussion

3.1. Materials properties

Particle-size distribution curves are shown in Fig. 4, and the corresponding size fractions and density values are summarised in Table 4. The three earth differ markedly in granulometric composition. Lv is the finest material, with the highest clay fraction, followed by Bh, whereas Rm contains a substantially lower clay content and a greater proportion of coarser particles.

The mineralogical composition obtained is presented in Table 5. Results show that Lv, derived from basaltic parent material, is characterized by a predominance of kaolinite (56.3 wt%), gibbsite (16.9 wt%), and iron oxides, mainly hematite (18.6 wt%) and maghemite (4.6 wt%). This assemblage is typical of highly weathered lateritic soils, where the leaching of silica and alkalis results in the enrichment of aluminium and iron residual phases. The presence of minor anatase (TiO_2) further supports an advanced stage of tropical weathering under warm and humid conditions [36,63–66].

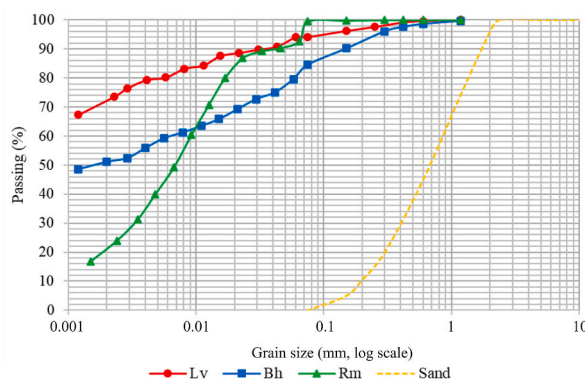


Fig. 4. Particle size distribution of sand, Lv, Bh, and Rm earth.

Table 4

Size fractions, particle and loose bulk density.

Material	Clay (%) [<0.002 mm]	Silt (%) [0.002-0.06 mm]	Sand (%) [0.06-2.36 mm]	Particle density (g/cm ³)	Bulk density (g/cm ³)
Lv	72	22	6	2.958	1.117
Bh	51	28	21	2.647	0.899
Rm	21	71	8	2.627	0.790
Sand	-	-	100	2.995	1.573

Table 5

Mineralogical composition of samples, expressed in weight percentage.

Mineral	Mineral group	Chemical composition	Samples (wt.%)			
			Earth			Sand
			Lv	Bh	Rm	
Kaolinite ^a	Phyllosilicates (1:1 kaolinite)	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	56.3	62.3	20.5	-
Clinocllore ^a	Phyllosilicates (2:1:1 chlorite)	$(\text{Mg}, \text{Fe}^{2+})_5\text{Al}(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_8$	-	-	10.6	-
Montmorillonite ^a	Phyllosilicates (2:1 smectite)	$(\text{Na}, \text{Ca})_{0-3}(\text{Al}, \text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$	<0.1	-	-	1.2
Vermiculite ^a	Phyllosilicates (2:1 vermiculite)	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	-	-	1.6	-
Calcite	Carbonates	CaCO_3	-	-	-	0.6
Gibbsite	Hydroxides	$\text{Al}(\text{OH})_3$	16.9	12.8	-	-
Goethite	Hydroxides	$\text{FeO}(\text{OH})$	-	11.2	-	-
Hornblende	Inosilicates (amphiboles)	$\text{Ca}_2[\text{Mg}_4(\text{Al}, \text{Fe}^{3+})]\text{Si}_7\text{AlO}_{22}(\text{OH})_2$	-	-	<0.1	-
Diopside	Inosilicates (pyroxene)	$\text{CaMgSi}_2\text{O}_6$	-	-	-	20.9
Anatase	Oxides	TiO_2	1.3	-	-	-
Hematite	Oxides	Fe_2O_3	18.6	0.8	-	-
Maghemite	Oxides	Fe_2O_3	4.6	-	-	-
Magnetite	Oxides	Fe_3O_4	-	<0.1	-	-
Muscovite	Phyllosilicates (mica)	$\text{KAl}_2(\text{Si}_3\text{Al})_{10}(\text{OH}, \text{F})_2$	-	-	4.7	-
Quartz	Tectosilicates	SiO_2	2.4	11.5	16.9	2.1
Albite	Tectosilicates (feldspar)	$\text{NaAlSi}_3\text{O}_8$	-	-	31.4	-
Anorthite	Tectosilicates (feldspar)	$\text{CaAl}_2\text{Si}_2\text{O}_8$	-	-	-	18.9
Labradorite	Tectosilicates (feldspar)	$(\text{Ca}, \text{Na})(\text{Si}, \text{Al})_4\text{O}_8$	-	-	-	56.3
Microcline	Tectosilicates (feldspar)	KAlSi_3O_8	-	1.5	14.3	-

^a Clay minerals.

The Bh mineralogical composition is dominated by kaolinite (62.3 wt%), with significant gibbsite (12.8 wt%) and goethite (11.2 wt %), accompanied by minor quartz (11.5 wt%) and microcline (1.5 wt%). Compared to Lv, Bh presents a slightly lower degree of oxidation (hematite being replaced by goethite), indicating a more hydrated and moderately oxidizing environment during soil formation [67]. In contrast, the Rm exhibits a markedly different mineralogical signature. It is dominated by feldspars, especially albite (31.4 wt%) and microcline (14.3 wt%), along with chlorite (10.6 wt%) and quartz (16.9 wt%). The lower kaolinite content (20.5 wt%) and the occurrence of minor vermiculite (1.6 wt%) indicate a heterogeneous and less weathered material, with a significant fraction of primary silicate minerals preserved from the parent rock [68]. The clay mineral assemblages reflect distinct degrees of weathering among the earth samples.

In terms of the clay minerals, Lv and Bh are both dominated by kaolinite, associated with gibbsite and iron oxides/hydroxides, indicating advanced lateritic weathering and the formation of low-activity clays typical of mature tropical soils. These minerals confer low plasticity, limited swelling, and high structural stability to the materials [69,70]. In contrast, the Rm sample exhibits a more heterogeneous and less evolved clay fraction, comprising kaolinite, chlorite, and minor vermiculite. This composition suggests incomplete mineral alteration and mixed-layer clay formation, consistent with its origin as a fine residue from the washing of gneiss aggregates.

The basaltic sand is composed mainly of labradorite (56.3 wt%), diopside (20.9 wt%), and anorthite (18.9 wt%), confirming its mafic and crystalline nature. The relative absence of clay minerals and the prevalence of plagioclase and pyroxene phases characterize it as a chemically stable and non-plastic material, playing a passive role in the mineralogical composition of the earthen mortars.

TGA/DTA graphs and the derivative thermogravimetric curve (DTG) of the raw material are presented in Fig. 5.

Results show that the total mass loss of the Lv sample, from room temperature up to 1000 °C, was approximately 18.2%. The first mass-loss event, occurring between 180 °C and 350 °C, is associated with the dehydroxylation of gibbsite [71,72]. In contrast, the main mass loss, registered between 350 °C and 560 °C, corresponds to the dehydroxylation of kaolinite and its transformation into meta-kaolinite, confirming the predominance of 1:1 phyllosilicates in the sample [73]. The Bh sample exhibited a similar thermal pattern and a very similar total mass loss (18.1%). Its DTG curve reveals the decomposition of goethite between 300 °C and 380 °C [74], followed by a central endothermic peak within the same range observed for kaolinite (350–560 °C), consistent with its kaolinite content. In contrast, the Rm sample displayed a single broad mass-loss event (5.3%) with a weak endothermic signal, indicating a low clay mineral content. Nonetheless, the subtle dehydroxylation feature between 350 °C and 560 °C suggests the presence of residual kaolinite in minor quantities, as revealed in XRD analysis. The basaltic sand presents a total mass loss of approximately 1%, a result

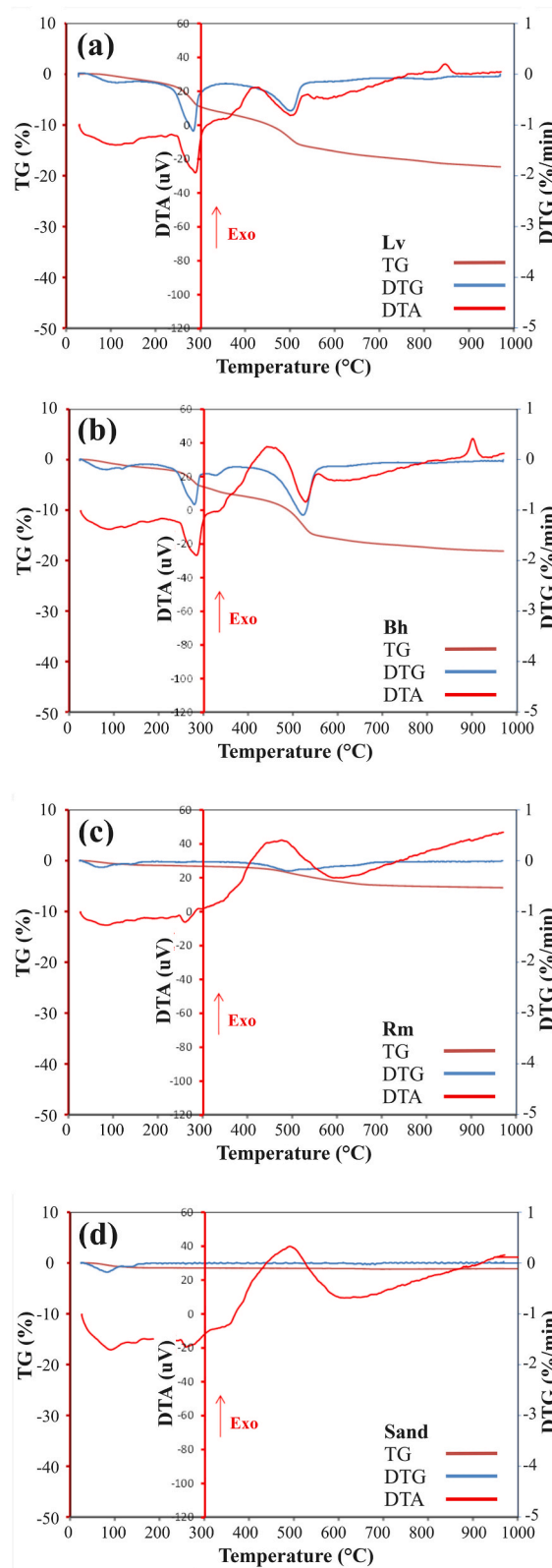


Fig. 5. Thermogravimetric (TG), derivative (DTG), and differential thermal analysis (DTA) curves of the samples: a) Lv, b) Bh, c) Rm, and d) Sand.

consistent with the mineralogical composition identified by XRD. The slight exothermic event, with a peak around 500 °C, is associated with the decomposition of minor calcite and montmorillonite traces, present in small amounts, since the primary minerals of the basaltic sand are thermally stable up to about 900–1000 °C [68,75].

The DTA curves of the samples are consistent with the DTG mass losses, except for samples Lv and Bh, which show an exothermic peak at ~900 °C attributed to the formation of a spinel aluminosilicate [76].

3.2. Fresh state mortars properties

Table 6 shows the fresh-state properties of the mortars, namely flow table consistence and wet density, for sets 1 and 2. Fig. 6 summarizes the relationships between clay content, fluidity index (FI), and wet density of the studied mortars. Since two experimental sets were carried out for each mix of each earth, Fig. 6 combines the parameters obtained from both sets.

Fig. 6a illustrates the effect of clay fraction on FI, showing a clear inverse relationship between the variables, with higher clay fractions leading to lower FI values. This trend indicates that mortars with elevated clay content require substantially more water to reach the target workability. For example, mortars produced with the Rm earth (low clay content, 7–21%) exhibit FI values above 700, corresponding to relatively low water demands to achieve the desired consistence. In contrast, mortars prepared with Bh and Lv earth (13–72% clay) exhibit progressively reduced FI values, indicating that higher water contents are required to compensate for the increased surface area and water absorption capacity of the clay minerals. These findings highlight the critical influence of clay content on water demand and workability: while clay-rich earth improve cohesion, they significantly reduce fluidity, as also observed by Luiz et al. [8]. Fig. 6b shows a strong positive correlation between FI and wet bulk density, which ranged from 1.66 to 2.22 g/cm³.

Denser mortars consistently exhibited higher FI values for the same target consistence, and the regression coefficients confirm the robustness of this trend across the three earth types. As summarised in Table 1, these density values fall within the general range (1.4–2.1 g/cm³) reported in the literature. Fig. 6c integrates clay content, FI, and wet density into a contour map for all mortars. The colour gradient illustrates how composition affects consistence and density, helping identify compositional ranges that achieve adequate workability with balanced water demand.

3.3. Porosity and bulk density of mortars

Fig. 7 presents the total open porosity (Fig. 7a) and bulk density (Fig. 7b) of the mortars measured on cylindrical and rectangular specimens. Total porosity ranges from 28.8% to 48.4%, with the highest values observed in the more clay-rich reference mixtures (>43%). These values are consistent with those reported by Santos et al. [5] (31.5%), Randazzo et al. [31] (34.1%), McGregor et al. [3] (33%) and Lima et al. [34] (33.9%) for mortars containing 19–31% clay. Most mortars in Table 1 present porosity between 20 and 30%, typical of coarser composites with lower clay contents. In this study, the most porous mixtures (>35%) correspond to finer particle-size distributions, while increasing the sand fraction (1:1 to 1:3) leads to a progressive reduction and stabilisation of porosity around 35–40%. Mortars formulated with Rm earth, characterised by lower clay contents, show the lowest porosity (28.8–33.4%). Differences between cylindrical and rectangular specimens are small and generally within experimental variation, suggesting that composition was the dominant factor controlling porosity within the present experimental programme. However, these results should be interpreted with caution, since the specimen geometries were prepared using different moulding and compaction procedures and, therefore, do not directly reproduce the manual application of a plaster onto a wall by trowelling. Accordingly, the porosity and density values reported here should be understood primarily as comparative indicators of the influence of composition under controlled laboratory preparation conditions, rather than as direct estimates of in-service plaster microstructure.

Bulk density follows the inverse trend, ranging from 1.42 to 2.03 g/cm³. Lower densities occur in clay-rich reference mortars, whereas sand-rich Rm mortars reach the highest values. Although literature values (Table 1) typically vary from 1.57 to 1.91 g/cm³, the higher densities observed here (>1.90 g/cm³) reflect the naturally denser Lv and Bh earth and the use of basaltic crushed sand (particle density 2.995 g/cm³), which exceeds the densities of river sands used in many studies. As with porosity, density differences between specimen geometries are limited (≤0.03 g/cm³), but they should be interpreted in light of the distinct specimen preparation

Table 6
Fresh mortar flow table consistence and wet density.

Mortar	Flow table consistence (mm)		Wet density (g/cm ³)	
	Set 1	Set 2	Set 1	Set 2
Lv-Ref	174 ± 1	-	1.68	-
Lv-1	175 ± 2	165 ± 3	1.93	1.95
Lv-2	179 ± 1	178 ± 0	2.00	2.06
Lv-3	180 ± 2	179 ± 1	2.06	2.11
Bh-Ref	169 ± 2	-	1.66	-
Bh-1	178 ± 1	169 ± 1	1.93	1.94
Bh-2	179 ± 2	175 ± 2	2.03	2.05
Bh-3	180 ± 2	173 ± 2	2.09	2.10
Rm-Ref	178 ± 2	-	1.74	-
Rm-1	178 ± 3	174 ± 2	2.09	2.08
Rm-2	172 ± 2	181 ± 3	2.22	2.21

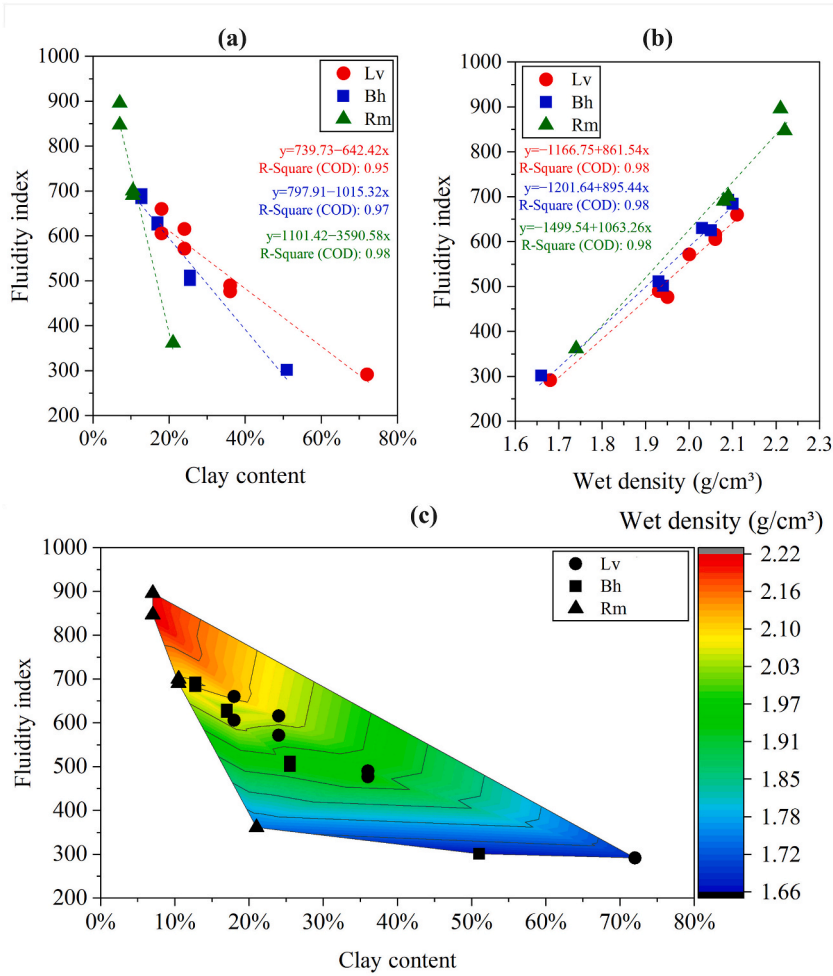


Fig. 6. Relationships between clay content, fluidity index, and wet density of earthen mortars: (a) FI versus clay content; (b) FI versus wet density; (c) contour map combining clay content, FI and wet density.

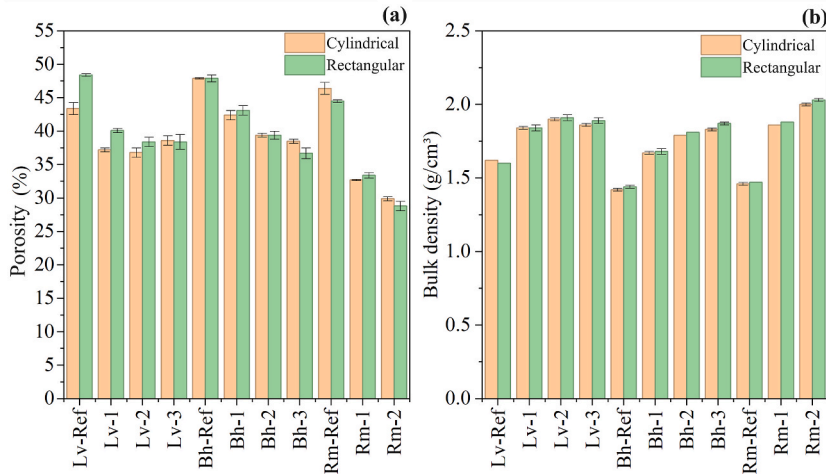


Fig. 7. Total open porosity (a) and bulk density (b) measured on cylindrical and rectangular specimens. Error bars represent standard deviation ($n = 3$). The compared specimen types were obtained using different moulding/compaction procedures; therefore, geometry and preparation conditions were not independent variables.

procedures adopted.

Complementing the analyses in Figure 7, Figure 8 confirms a strong inverse linear relationship between bulk density and total porosity across the three mortar groups.

Fig. 8b and c further show that, despite compositional differences among the earth, lower clay content and higher FI consistently lead to higher bulk density and reduced porosity, indicating more efficient particle rearrangement and compaction during moulding. These trends are confirmed within each group: in Lv mortars, bulk density increases from 1.6 to 1.9 g/cm³ while porosity decreases from 43–48% to 37–39% as FI rises and clay content decreases. Similar behaviour is observed in Bh and Rm mixtures, where density increases from 1.4 to 1.5 to 1.9–2.0 g/cm³ and porosity drops from ~48% to 29–37%. These values quantitatively illustrate the relationships identified in Figure 8b and c and reflect the lower water demand and more efficient particle packing of mortars with reduced clay fractions. Therefore, the relationships shown in Fig. 8 are considered robust in relative terms, as they consistently reflect the effects of clay fraction, water demand and packing efficiency, although absolute porosity and density levels may differ from those developed under real wall application conditions.

3.4. Linear and volumetric shrinkage of mortars

Fig. 9 shows the 14-day evolution of LS for circular specimens (c) and the mean 14-day LS values for prismatic sand-stabilised mortars (p). During the first day, LS ranges from 1.0 to 2.3%, with reference mortars showing the highest values, although no clear trend is observed among the sand-corrected formulations. Most deformation occurs within the first seven days, followed by a stabilisation phase in which variations remain below 0.1%, consistent with the early normal-shrinkage stage described by Leong and Wijaya [77] and the behaviour reported by Delinière et al. [27] and Narloch and Woyciechowski [78]. This rapid stabilisation indicates that water loss and particle rearrangement are largely completed during the early curing period.

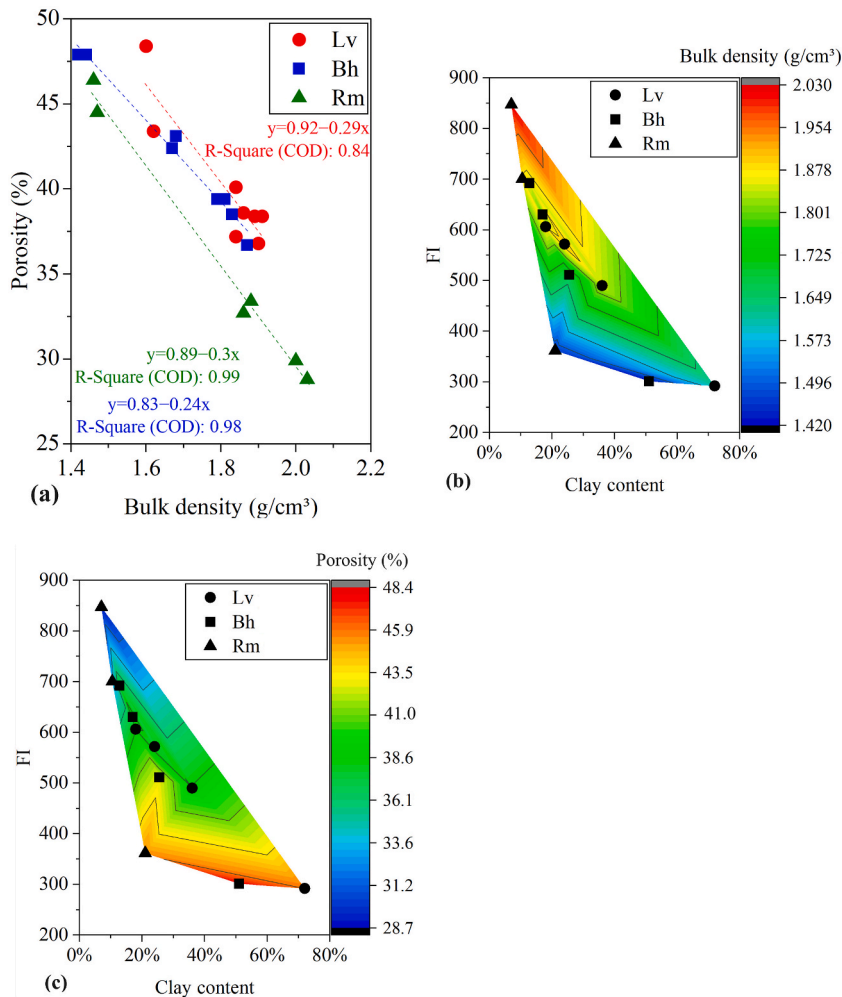


Fig. 8. Correlation between total porosity and bulk density (a), and of clay content with both bulk density (b) and porosity (c) for the three earthen mortar groups (Lv, Bh, and Rm).

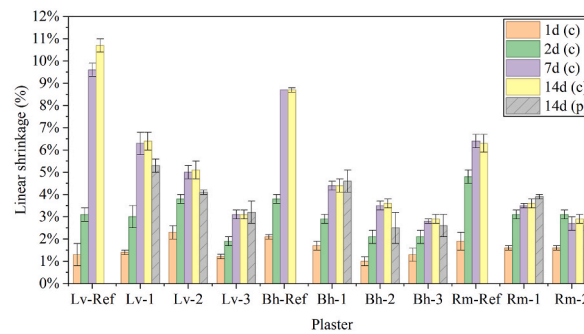


Fig. 9. Linear shrinkage behaviour of Lv, Bh, and Rm mortars at different ages. Results identified as (c) were obtained from circular specimens, whereas (p) correspond to prismatic specimens at 14 days. Error bars represent standard deviation ($n = 3$). Comparisons between (c) and (p) results should consider that specimen geometry and moulding/compaction procedure were not independent variables.

At 14 days, LS ranges from 2.9% to 10.7%, with the highest values observed in the clay-rich reference mortars and the lowest in the sand-rich ones. The magnitude of reduction depended on both earth type and mix ratio: the 1:1 proportion produced moderate decreases (40–49% for Lv and Bh, respectively), while the 1:2 mixes achieved more substantial reductions (52–59% for Lv and Bh, respectively), representing an effective balance between shrinkage control and formulation feasibility. The most significant improvements occur in the 1:3 mortars of Lv and Bh, where shrinkage decreases by 67–71% (Bh–Lv), reaching values of nearly 3%. For Rm, characterised by lower clay content, the maximum reduction is 54% in the 1:2 mortar. These results align with the literature [24, 27, 32], which consistently identifies the clay fraction as the primary driver of shrinkage in earthen composites.

The LS values obtained in this study reached up to 10.7%, corresponding to the upper limit of the 3–12% range reported by Minke [57] for earthen mortars and bricks. Hamard et al. [32] reported LS values between 4% and 17% for French clays with clay contents ranging from 3% to 18%, whereas most studies compiled in Table 1 reported LS values below 4%, particularly for formulations richer in coarse particles or low-activity clays. Gomes et al. [24] obtained LS values below 1.5% using illitic-kaolinitic clays, with clay contents between 10% and 19%. These results were substantially lower than those measured for the tested Lv-3 and Bh-3 mortars, with earth which are predominantly kaolinitic and rich in iron oxides, with clay contents of 18% and 13%, respectively. The LS values of 3.1% for Lv-3 and 2.9% for Bh-3 therefore indicate a markedly higher shrinkage compared to the results of Gomes et al. [24], despite the similar clay contents. Likewise, the values obtained in the present study are slightly higher than those reported by Delinière et al. [27], who worked with earth containing 8–11% clay and recorded LS between 1.5% and 2.5%.

From a practical standpoint, these results are particularly relevant because, even after sand correction, most LS values remain above the 2% limit established by DIN 18947 [23] for earthen plasters. This indicates that, although sand addition substantially improves dimensional stability, shrinkage-related cracking may still represent a significant application constraint, especially for clay-richer formulations. In practical terms, these mortars may require stricter control of substrate suction, layer thickness, drying conditions and workmanship during wall application, and in some cases additional formulation adjustments may be needed to reduce cracking susceptibility. Therefore, the present results highlight that compliance with shrinkage limits cannot be assumed solely from sand correction and must be verified for each earth type, particularly with tropical materials with fine and cohesive matrices.

Among the mortars analysed, Rm-2 exhibits the highest shrinkage relative to its clay content, despite presenting the lowest clay fraction of all samples (7%). This behaviour is attributed to its more active clay fraction, composed of 2:1 minerals such as chlorite and vermiculite, which display interlayer swelling capacity. For mortars with similar clay contents to Rm-2, other authors have reported significantly lower shrinkage values, typically below 1.5% or even near zero, as observed by Santos et al. [5], Delinière et al. [27], and Pachamama et al. [17]. These comparisons further reinforce the influence of mineralogical composition over total clay percentage, demonstrating that 2:1 clays, even in small proportions, can substantially increase linear shrinkage in earthen mortars.

These other studies, conducted with non-tropical earth from Portugal and France, contrast with the tropical earth types Lv and Bh investigated here. As noted by Pachamama et al. [17], Portuguese earthen mortars with similar sand additions and clay fractions tend to exhibit lower LS than Brazilian ones, a difference attributed to the mineralogical composition of Mediterranean soils, which are characterized by lower expansivity and a higher liquid limit due to reduced silt content. The Lv and Bh earth types, though dominated by kaolinite, also contain iron oxides, imparting a fine and cohesive microstructure that enhances capillary tension and drying sensitivity. As a result, even with moderate clay contents (approximately 18% for Lv-3 and 13% for Bh-3), both mortars show slightly elevated shrinkage compared with European counterparts.

Comparison of the two specimen types (c and p) allows assessing the influence of ambient humidity on shrinkage. In the Lv mortars, LS in prismatic specimens is slightly lower for Lv-1 and Lv-2, indicating greater sensitivity to humidity in the clay-rich mixtures, while Lv-3 shows equivalent values in both conditions, reflecting reduced sensitivity at lower clay contents. The behaviour of the Bh mortars is less uniform: Bh-1 exhibits similar LS in both environments, Bh-2 shows slightly lower values in prismatic specimens, and Bh-3 follows the trend of Lv-1, with reduced shrinkage under high humidity. For the Rm mortars, LS values are nearly identical across environments, with extensive overlap of error bars, confirming minimal hygroscopic sensitivity and high dimensional stability. Overall, the influence of ambient humidity increases with clay content and plasticity: Lv and Bh mortars respond more strongly to drying conditions, whereas Rm mortars remain largely unaffected due to their lower clay content and higher sand proportion. For this

reason, LS alone is not sufficient to fully describe the dimensional instability of the mortars, and its interpretation is complemented by the volumetric shrinkage results discussed below and summarised in Table 7.

Fig. 10 and Table 7 show that VS is systematically higher than LS for all formulations, reflecting the three-dimensional nature of drying contraction. This systematic comparison confirms that VS is a more sensitive parameter than LS, since it captures shrinkage differences among formulations more clearly and reveals volumetric changes that are only partially reflected in one-dimensional measurements. As observed by Gomes et al. [24], LS alone may underestimate the total magnitude of drying deformation, particularly in clay-rich mortars. The relative reductions in VS at 14 days show clear differences among earth types and sand ratios. For Lv, VS decreases progressively with sand addition, from 37% (1:1) to 60% (1:2) and 79% (1:3), indicating a strong and continuous stabilizing effect. Bh mortars follow the same trend, with substantial reductions of 53% (1:1), 62% (1:2) and 70% (1:3). In contrast, Rm shows a more limited response, with reductions of 42% (1:1) and 51% (1:2). The absolute VS values obtained in this study fall within the broad range reported in the literature, where volumetric shrinkage generally varies from about 2.5% to 22%, depending on clay content and mineralogy [24,25].

The VS/LS ratio in this study ranges from 2.0 to 3.3, confirming that volumetric shrinkage is two to three times greater than linear shrinkage. For Lv and Bh, this ratio decreases with sand addition, indicating that stabilisation reduces both the magnitude of deformation and its directional anisotropy. Mineralogy largely governs these trends. Rm mortars exhibit the highest VS/LS ratios (>3.0), which remain stable or increase with sand incorporation. This behaviour is attributed to the presence of clinocllore and vermiculite, whose swelling mechanisms - external surface hydration for clinocllore and interlayer expansion for vermiculite - promote significant volumetric deformation even when LS remains moderate [79–81]. Their combined action in a feldspathic–chloritic matrix leads to the atypical combination of low LS and high VS observed in the Rm group.

In contrast, Lv and Bh mortars, dominated by kaolinite and iron oxides, show progressively lower VS/LS ratios with increasing sand. Kaolinite's stable 1:1 structure limits swelling, while iron and aluminium oxides promote particle aggregation and microstructural cementation [82–85], reducing pore collapse and capillary-induced deformation. As a result, these mortars exhibit more moderate and directional shrinkage, differing from the more isotropic volumetric response seen in Rm mortars.

Fig. 11 shows the relationships between bulk density and LS (Fig. 11a) and VS (Fig. 11b) for the Lv, Bh, and Rm mortars, with dashed lines indicating the linear fits. In general, both shrinkage parameters decrease with increasing bulk density, indicating that denser mixtures undergo smaller dimensional changes during drying. Lv mortars exhibit the highest shrinkage values due to their lower density and higher clay content, whereas Bh and Rm mortars show reduced shrinkage, reflecting greater compactness and structural stability.

Although this trend is general, mineralogy modulates its intensity. In kaolinite and iron oxide-rich mortars (Lv and Bh), reduced porosity corresponds to limited shrinkage due to the non-expansive nature of kaolinite and the cementing effect of oxides. In contrast, in the Rm mortars, despite their higher density, the presence of expansive minerals such as vermiculite and clinocllore promotes localized swelling and internal stress development, which may offset the stabilizing effect of densification. This behaviour reinforces the importance of considering VS together with LS when assessing shrinkage sensitivity, since one-dimensional measurements alone may underestimate the extent of drying deformation in mortars containing mineral phases capable of promoting volumetric instability.

3.5. Mechanical characterization of mortars

Fig. 12 presents the mean FStr and CStr values of the mortars. Reference mortars were excluded due to excessive shrinkage. Larger standard deviations in the Lv and Bh groups indicate higher sensitivity to microstructural heterogeneity and moisture variation, while Rm mortars show more consistent responses.

The variability observed in mechanical performance arises partly from minor differences in specimen preparation and microstructural heterogeneity, but it is mainly driven by moisture differences among specimens stored under high-humidity conditions. Although all samples were moulded using the same procedure, small variations in grain distribution, clay content and porosity, combined with slight temperature and humidity gradients in the chamber, caused each specimen to absorb moisture differently. As a result, moisture contents within the same mortar group varied by 0.7–1.7%, producing significant differences in degree of saturation.

Table 7

Summary comparison between 14-day linear shrinkage (LS) and volumetric shrinkage (VS), including their relative reductions with respect to the reference mortars.

Mortar	LS (%)	VS (%)	VS/LS	LS reduction vs. reference (%)	VS reduction vs. reference (%)
Lv-Ref	10.7 ± 0.3	29.7 ± 0.5	2.8	–	–
Lv-1	6.4 ± 0.4	18.7 ± 1.0	2.9	40	37
Lv-2	5.1 ± 0.4	12.0 ± 0.4	2.4	52	60
Lv-3	3.1 ± 0.2	6.3 ± 0.6	2.0	71	79
Bh-Ref	8.7 ± 0.1	24.5 ± 1.1	2.8	–	–
Bh-1	4.4 ± 0.3	11.4 ± 0.4	2.6	49	53
Bh-2	3.6 ± 0.2	9.4 ± 0.1	2.6	59	62
Bh-3	2.9 ± 0.2	7.4 ± 1.0	2.6	67	70
Rm-Ref	6.3 ± 0.4	19.4 ± 1.3	3.1	–	–
Rm-1	3.6 ± 0.2	11.3 ± 0.5	3.1	43	42
Rm-2	2.9 ± 0.2	9.5 ± 1.2	3.3	54	51

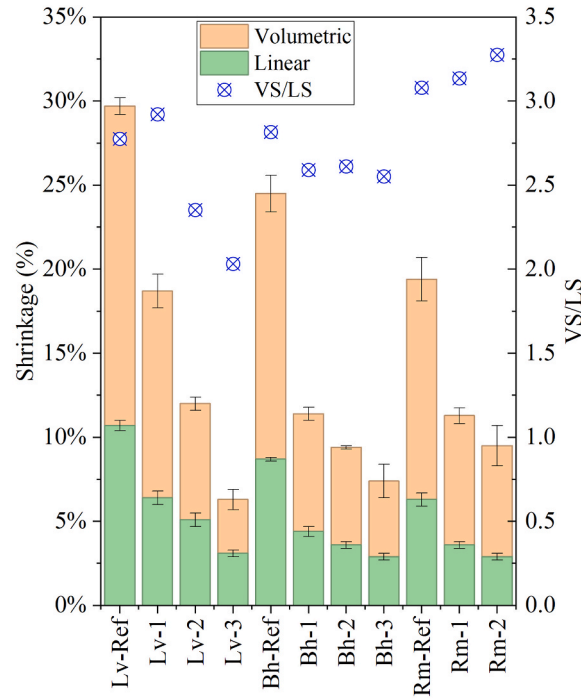


Fig. 10. Linear shrinkage, volumetric shrinkage, and VS/LS ratio of earthen mortars at 14 days. Error bars represent standard deviation ($n = 3$). Comparisons between LS and VS should consider that these parameters were obtained from different specimen geometries prepared under distinct moulding/compaction procedures.

These variations directly affect strength, since water content controls particle bonding and effective stress in the porous matrix [86–88]. Thus, specimens with identical mix proportions can exhibit different mechanical responses simply due to differences in residual moisture at the time of testing.

In unsaturated earthen materials, the coexistence of air and water in the pore network generates negative pore-water pressure (matric suction), which governs key behaviours such as swelling, shrinkage and mechanical strength under different moisture conditions [89]. The degree of saturation (S_r) is therefore a fundamental parameter, as it reflects the proportion of pore volume filled with water and directly controls the interparticle forces responsible for cohesion, stiffness and load-bearing capacity. S_r expresses the ratio between the volume of water (V_w) and the total void volume (V_v) in a soil/earth mass and can be estimated indirectly from measurable physical parameters using Eq. (1), where w is the gravimetric water content (ratio between the mass of water and the mass of solids), ρ_s is the particle density of soil (g/cm^3), e is the void ratio (ratio between the volume of voids and the volume of solids), and ρ_w is the density of water, considered as $0.998 \text{ g}/\text{cm}^3$, corresponding to a temperature of 20°C .

$$S_r = \frac{\rho_s \cdot w}{\rho_w \cdot e} \quad \text{Eq. 1}$$

To demonstrate how moisture fluctuations affect mechanical performance, Fig. 13 shows the individual FStr and CStr values of the Lv (Fig. 13a), Bh (Fig. 13b) and Rm (Fig. 13c) mortars as a function of S_r . The dashed lines correspond to linear fits, highlighting how closely the experimental data follow the moisture–strength trend.

The Lv and Bh groups (Fig. 13a and b) show similar moisture–strength trends. At low S_r (high matric suction), CStr is higher than FStr in the Lv-1 and Bh-1 mortars; however, as S_r increases and suction decreases, the curves intersect and FStr becomes higher (more clearly in Lv-1). In Lv-3 and Bh-3, the curves converge and local regions with $\text{FStr} > \text{CStr}$ appear, although the crossover is less evident in Bh-3. For the intermediate mixes (Lv-2 and Bh-2), the lines do not intersect within the measured S_r range, but their progressive approximation suggests that inversion could occur under slightly lower saturation. These behaviours confirm that matric suction (inversely related to S_r) governs the relative magnitude of FStr and CStr: as suction decreases, CStr drops more sharply than FStr, as previously observed by Ajaz & Parry [90]. Consequently, when averaging results from specimens stored under high humidity (without explicitly accounting for variations in S_r) mean FStr values tend to exceed mean CStr, as seen in Fig. 12. This indicates that compressive strength is more sensitive to suction loss than flexural strength under humid conditions.

A plausible explanation for this behaviour is that compressive strength in unsaturated earthen mortars depends more strongly on the contribution of matric suction and capillary bonding to the effective confinement of the granular-clay skeleton. As saturation increases, the progressive reduction of suction weakens meniscus forces at particle contacts and reduces the apparent cohesion that stabilises the load-bearing network, leading to a marked loss of compressive resistance. In flexure, although suction also contributes to

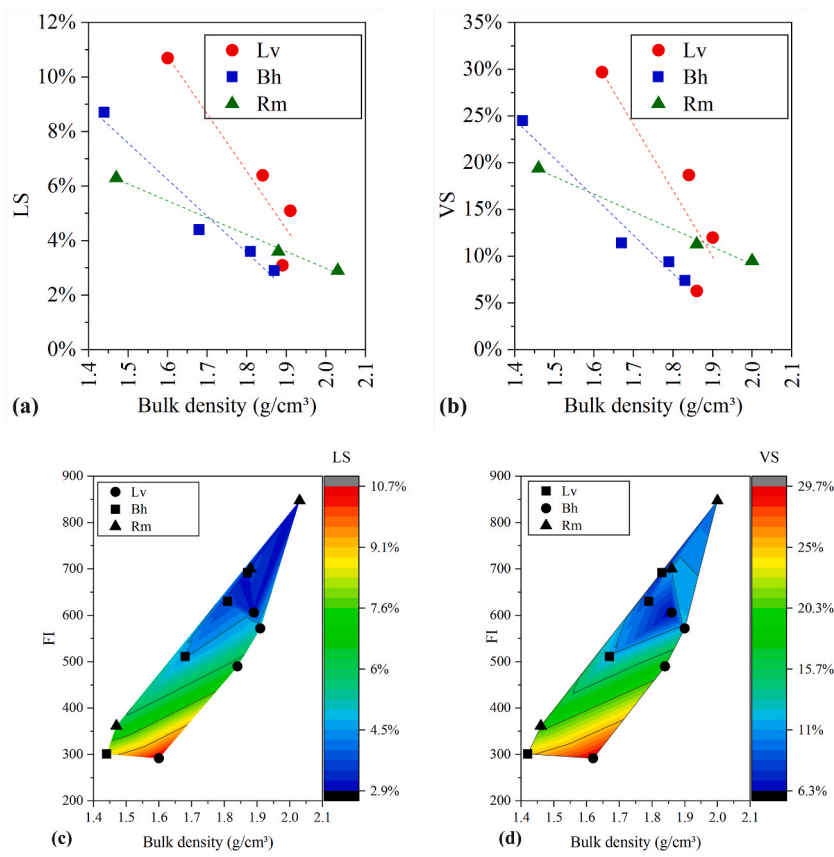


Fig. 11. Relationship between bulk density and shrinkage: (a) linear; (b) volumetric; contour maps showing the relationship among FI, bulk density, and LS (c); and among FI, bulk density, and VS (d). LS and VS were obtained from different specimen geometries/preparation routes.

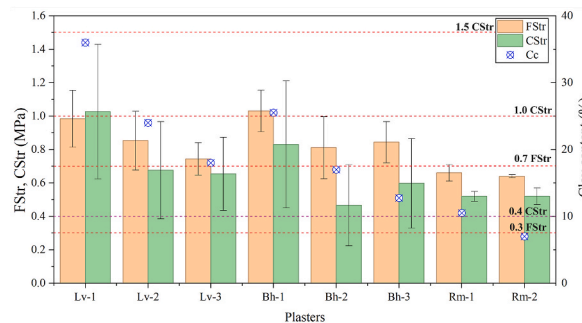


Fig. 12. Flexural strength (FStr) and compressive strength (CStr) of mortars at 14 days as a function of clay content (Cc, right axis). Error bars represent standard deviation (n = 4). Horizontal reference lines indicate strength thresholds from DIN 18947 and EN 998-1.

strength, failure is governed by tensile cracking localised in a narrower zone, and the residual interparticle bonding may remain sufficient to sustain moderate FStr values even after substantial suction loss. Under high-humidity conditions, this differential sensitivity causes CStr to decrease faster than FStr, which can result in local or average cases where FStr exceeds CStr, which is positive for plastering mortars. Therefore, the inversion observed here should not be interpreted as an anomalous intrinsic superiority of flexural performance, but rather as a consequence of the distinct way in which increasing saturation affects the two failure modes in unsaturated earthen mortars.

In the literature, CStr of earthen products is generally reported to be higher than FStr [5,15,24,27,30,91], as is also common for many other building products. The results obtained here differ from this usual trend, which is likely related not to a fundamentally different failure mechanism, but to the high-humidity condition under which the specimens were tested and to the greater sensitivity of CStr to suction loss in the unsaturated state. Typically, previous studies evaluated specimens under intermediate temperature and

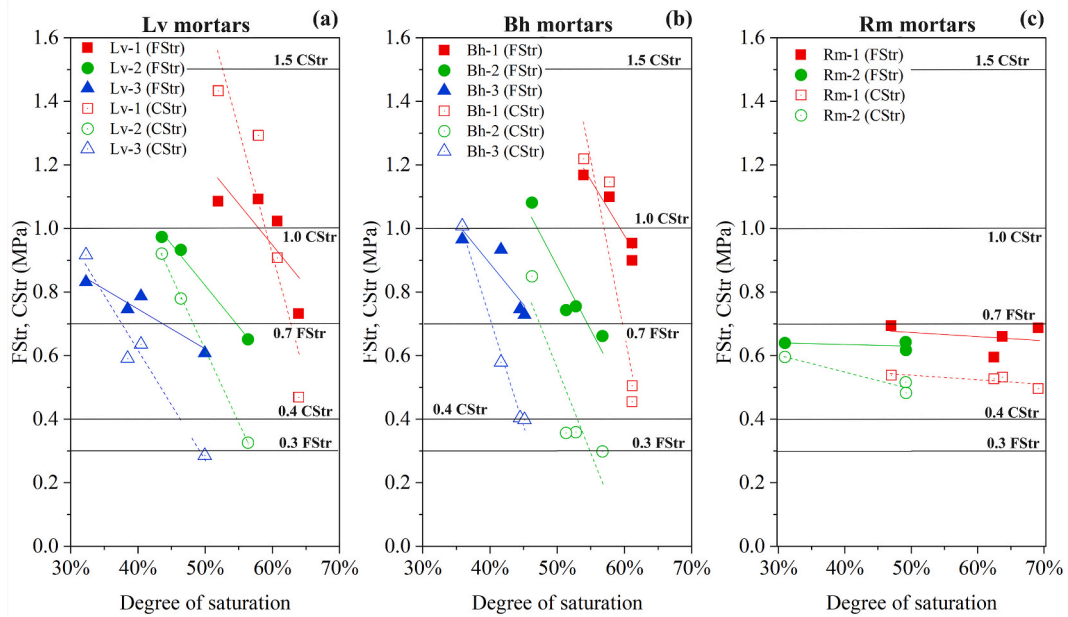


Fig. 13. Influence of degree of saturation on flexural and compressive strength of a) Lv, b) Bh, and c) Rm mortars. Horizontal reference lines indicate strength thresholds from DIN 18947 and EN 998-1.

humidity conditions ($23 \pm 2^\circ\text{C}$ and $50 \pm 5\%$ RH), in which equilibrium with the environment corresponded to relatively low moisture contents, thus representing low degrees of saturation. In contrast, the present study investigates specimens under high-humidity conditions, where the pores of the mortars are partially filled with water, characterizing an unsaturated state. In this regime, suction contributes to strength through both the tensile effect associated with negative pore-water pressure and the capillary bonding generated by water menisci at the air–water interface, which together form an important part of the apparent cohesion of unsaturated earthen materials [29].

Considering the individual FStr and CStr values with respect to the DIN 18947 [23] limits - class SI (CStr ≥ 1.0 MPa; FStr ≥ 0.3 MPa) and class SII (CStr ≥ 1.5 MPa; FStr ≥ 0.7 MPa) - the mortars show distinct performance patterns across the three earth types. In the Lv group, only Lv-1 reaches CStr values above 1.0 MPa, satisfying class SI and locally approaching the 1.5 MPa threshold of class SII, though only at lower saturation levels ($\approx 50\%$). Lv-2 and Lv-3 remain below 1.0 MPa and therefore do not meet the compressive criterion. All Lv mortars show FStr above 0.3 MPa (class SI), with only Lv-1 locally reaching the 0.7 MPa limit for class SII. In the Bh group, Bh-1 displays the highest strengths: all FStr values are above 0.7 MPa (SII), and CStr values exceed 1.0 MPa (SI), although none reach 1.5 MPa. Bh-2 and Bh-3 satisfy the SI flexural criterion (0.3–0.7 MPa), but their CStr remains below 1.0 MPa. In the Rm mortars, no sample meets the CStr requirements for SI or SII, as all compressive strengths remain below 1.0 MPa across the tested saturation range. However, FStr consistently surpasses 0.3 MPa (SI), and several points approach or slightly exceed 0.7 MPa, partially meeting the SII flexural limit. However, in comparison to the EN 998-1 [92] standard for plastering and rendering mortars, all mortars meet the lower limit of 0.4 MPa in their average CStr values (Fig. 12).

The mortars Lv-3, Bh-3, and Rm-2, comparable in clay content to the Brazilian formulation evaluated by Pachamama et al. [17], show average FStr values of 0.74 MPa, 0.84 MPa, and 0.64 MPa, and CStr values of 0.65 MPa, 0.60 MPa, and 0.52 MPa, respectively. FStr values obtained in the present study are higher than those reported by Pachamama et al. [17] (0.4 MPa), even though the specimens in the present work have been tested under high-humidity conditions, which are generally unfavourable for mechanical performance. Conversely, CStr of the mortars developed in the present study are slightly lower than that reported by Pachamama et al. [17] (0.7 MPa). Overall, the comparison suggests that the tropical earth examined here exhibit mechanical stability under wet conditions comparable to or exceeding that of Brazilian reference earth tested in the dry state [17]. This comparison reinforces that the relative balance between FStr and CStr is strongly moisture-dependent and that, under wet unsaturated conditions, compressive performance may deteriorate more severely than flexural one.

Table 8 presents the slope (a), intercept (b), coefficient of determination (R^2) and the 95% confidence interval of the slope for the linear fits shown in Fig. 13. Overall, the fitted slopes are negative for both FStr and CStr in all mortar groups, indicating a general tendency for strength to decrease as the degree of saturation (Sr) increases. This behaviour is consistent with the strong influence of moisture on the mechanical performance of unstabilised earthen mortars, since increasing water content reduces matrix suction and weakens capillary forces, thereby lowering apparent cohesion and strength [4,28,29,86–89,91]. However, the confidence intervals show that the robustness of this linear relationship varies among mortars and between strength metrics. In several cases, the 95% confidence interval of the slope includes zero, indicating that, although the fitted trend is negative, the strength of the Sr–strength relationship should be interpreted with caution. For a more detailed visual representation of the uncertainty associated with the fitted

Table 8

Flexural (FStr) and compressive (CStr) strengths linear fitting parameters as a function of degree of saturation (Sr), including 95% confidence intervals for the slope.

Mortar	FStr			CStr		
	a [CI95%]	b	R ²	a [CI95%]	b	R ²
Lv-1	−2.59 [−9.05; 3.88]	2.50	0.60	−7.87 [−17.64; 1.90]	5.64	0.86
Lv-2	−2.60 [−5.76; 0.57]	2.12	0.99	−4.61 [−5.60; −3.62]	2.92	1.00
Lv-3	−1.25 [−2.53; 0.03]	1.25	0.90	−3.45 [−5.67; −1.23]	2.00	0.96
Bh-1	−3.48 [−6.77; −0.18]	3.06	0.91	−10.93 [−25.14; 3.28]	7.23	0.85
Bh-2	−4.02 [−8.53; 0.49]	2.89	0.88	−5.34 [−13.21; 2.52]	3.23	0.81
Bh-3	−2.59 [−6.74; 1.55]	1.93	0.78	−6.76 [−8.54; −4.99]	3.42	0.99
Rm-1	−0.13 [−1.53; 1.27]	0.74	0.08	−0.15 [−0.54; 0.25]	0.61	0.56
Rm-2	−0.05 [−1.58; 1.48]	0.66	0.16	−0.53 [−2.54; 1.47]	0.76	0.92

Note: Linear fits were expressed as $y = a \cdot S_r + b$, where a is the slope and b is the intercept. Values in brackets indicate the 95% confidence interval of the slope.

regressions, including the 95% confidence bands of the mean response, the reader is referred to the [Supplementary Material](#).

In the Lv and Bh groups, the negative effect of Sr is more clearly supported in specific cases, particularly for CStr in Lv-2, Lv-3 and Bh-3, and for FStr in Bh-1, where the 95% confidence intervals of the slope do not include zero. In the remaining Lv and Bh cases, the fitted slopes are also negative, but their confidence intervals overlap zero, suggesting greater uncertainty in the magnitude of the relationship despite moderate to high R² values. This indicates that moisture is an important controlling factor, but that its effect is modulated by compositional and microstructural differences among mortars.

In contrast, Rm mortars exhibit the weakest dependence of strength on Sr. Their fitted slopes are close to zero for both FStr and CStr, and all corresponding 95% confidence intervals include zero, indicating that no robust linear dependence on Sr can be inferred from the present data. This comparatively stable behaviour is consistent with their feldspathic–chloritic composition and lower clay fraction. Clinocllore, a 2:1:1 phyllosilicate with a magnesium hydroxide interlayer sheet, restricts interlamellar swelling and confines hydration mainly to external surfaces [81], which may help preserve interparticle bonding under wetter conditions. Although small amounts of vermiculite may introduce some swelling potential [80], the denser and coarser-grained matrix likely limits capillary-driven stress redistribution. Therefore, for Rm mortars, the results suggest that strength is less sensitive to changes in Sr within the tested range, although this interpretation should remain cautious given the wide confidence intervals and limited number of data points.

3.6. Inferential analysis of mortars' group differences

Table 9 summarizes the outcomes of the Welch's t-tests performed to evaluate differences between the assessed conditions. For each mortar, the table reports the difference between means (Δm), the t statistic, the Welch–Satterthwaite degrees of freedom (df), and the corresponding p-value for (i) porosity and (ii) LS when comparing 7 versus 14 days.

Statistically significant differences in porosity were observed only between cylindrical and rectangular specimens for Lv-ref, Lv-1, and Lv-2; the remaining formulations showed no evidence of differences at the 5% level. These findings may indicate a greater sensitivity of these mixes to moulding conditions. However, the comparison cannot be attributed solely to specimen geometry, as the preparation protocol differed between specimen types (higher compaction energy for cylindrical specimens and manual compaction for rectangular specimens). Accordingly, the observed differences reflect the combined influence of specimen preparation and geometry on porosity, rather than a geometry effect in isolation. Regarding LS, a statistically significant difference was observed only between 7 and 14 days for Lv-ref, whereas the other formulations showed no evidence of a difference over this interval. The negative

Table 9

Summary of Welch's t-tests.

Mortar	Porosity (cylindrical-rectangular)					LS (7d-14d)				
	Δm (%)	t	df	p-value	Sig.	Δm (%)	t	df	p-value	Sig.
Lv-ref	−5.0	−9.4	2.2	0.011	Yes	−0.011	−4.5	4.0	0.011	Yes
Lv-1	−2.9	−11.8	4.0	<0.001	Yes	−0.001	−0.3	3.8	0.804	No
Lv-2	−1.6	−2.8	4.0	0.049	Yes	−0.001	−0.4	3.7	0.752	No
Lv-3	+0.2	0.3	3.4	0.808	No	0.000	0.00	4.0	1.000	No
Bh-ref	0.0	0.0	2.2	1.000	No	0.000	0.00	2.0	1.000	No
Bh-1	−0.7	−1.2	4.0	0.288	No	0.000	0.00	3.5	1.000	No
Bh-2	0.0	0.0	2.9	1.000	No	−0.001	−0.6	4.0	0.573	No
Bh-3	+1.8	3.7	2.6	0.068	No	−0.001	−0.8	2.9	0.520	No
Rm-ref	+1.9	3.6	2.2	0.070	No	+0.001	0.4	3.7	0.752	No
Rm-1	−0.7	−2.9	2.2	0.099	No	−0.001	−0.8	2.9	0.520	No
Rm-2	+1.1	2.5	2.7	0.129	No	−0.002	−1.0	3.5	0.408	No

Δm indicates slightly higher LS at 14 days than at 7 days, suggesting that shrinkage in Lv-ref may continue to develop beyond the first week under the tested drying conditions. For the remaining mixes, the non-significant results are consistent with LS being broadly stable after 7 days within the experimental variability for the available sample size. Given $n = 3$ and the multiple comparisons performed, this finding should be interpreted cautiously and without extrapolation beyond the present test conditions.

4. Conclusions

This study examined physical and mechanical performance of non-binder stabilised tropical earthen plastering mortars produced from three distinct tropical earth types with diverse clays and contents (Lv and Bh, both highly weathered lateritic soils, and Rm, a fine residue from gneiss aggregate washing) and total particle-size distributions, changing the content of added sand (proportions of 1, 2 and 3 vol of sand added, in precise mass, to the earth). The results show that clay fraction, mineralogical assemblage, particle packing and moisture condition jointly control the behaviour of these mortars.

Lv and Bh mortars, characterised by finer fractions and predominance of kaolinite associated with iron and aluminium oxides, exhibited higher water demand, lower bulk density, higher porosity and greater shrinkage, with these effects being more pronounced in the reference and 1:1 mortars. Sand correction promoted clear matrix densification and significantly reduced both linear and volumetric shrinkage, with the strongest effect observed in Lv-3 and Bh-3. However, even the best-performing formulations remained above 2% linear shrinkage, indicating that shrinkage control remains a key challenge in plaster application. Volumetric shrinkage proved more sensitive than linear shrinkage, particularly in mortars containing 2:1 clay minerals. Under high-humidity conditions, compressive strength generally decreased more sharply than flexural strength with increasing saturation, highlighting the strong moisture dependence of mechanical performance.

Overall, the results indicate that tropical earthen mortars can be technically promising for low-impact plaster applications. However, their practical use depends on further optimisation of dimensional stability and moisture-sensitive performance. Future work should therefore focus on formulation improvements, including reinforcement strategies and compatible additions, as well as on the systematic consideration of moisture state in mechanical assessment. More broadly, the findings show that the performance of unstabilised tropical earthen plastering mortars cannot be interpreted solely based on earth type or mixture proportions taken separately, but rather as the result of the combined effects of clay fraction, mineralogical assemblage, sand correction, particle packing, and moisture condition. In this sense, the study provides a more context-sensitive basis for selecting and formulating earthen mortars for humid or seasonally wet tropical conditions, while also highlighting the need for further improvements in shrinkage control and moisture-resilient mechanical performance.

CRediT authorship contribution statement

Augusto Montor Freitas Luiz: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Antônio Penido Rezende:** Supervision, Funding acquisition. **Antônio Santos Silva:** Writing – review & editing, Validation, Methodology. **Paulina Faria:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.job.2026.116109>.

Data availability

Data will be made available on request.

References

- [1] A. Sánchez-Calvillo, L. Rincón, E. Hamard, P. Faria, Bibliometric analysis on earthen building: approaches from the scientific literature and future trends, *Buildings* 14 (2024) 3870, <https://doi.org/10.3390/buildings14123870>.
- [2] T. Santos, P. Faria, J. Sotomayor, J.D. Silvestre, A. Santos Silva, Effect of different surface treatments on the performance of Earth plasters, *Coatings* 14 (2024) 1537, <https://doi.org/10.3390/coatings14121537>.
- [3] F. McGregor, T. Mauffré, M.-S. Force, E. Contraires, A. Fabbri, Measurement of the water vapour permeability of earth plasters using small-scale wind tunnels under variable air flow regimes, *Mater. Struct.* 55 (2022) 110, <https://doi.org/10.1617/s11527-022-01950-8>.
- [4] L. Laou, J.E. Aubert, S. Yotte, P. Maillard, L. Ulmet, Hygroscopic and mechanical behaviour of earth bricks, *Mater. Struct.* 54 (2021) 116, <https://doi.org/10.1617/s11527-021-01701-1>.
- [5] T. Santos, M.I. Gomes, A.S. Silva, E. Ferraz, P. Faria, Comparison of mineralogical, mechanical and hygroscopic characteristic of earthen, gypsum and cement-based plasters, *Constr. Build. Mater.* 254 (2020) 119222, <https://doi.org/10.1016/j.conbuildmat.2020.119222>.
- [6] Y. Jiang, A. Phelipot-Mardele, F. Collet, C. Lanos, M. Lemke, M. Ansell, A. Hussain, M. Lawrence, Moisture buffer, fire resistance and insulation potential of novel bio-clay plaster, *Constr. Build. Mater.* 244 (2020) 118353, <https://doi.org/10.1016/j.conbuildmat.2020.118353>.
- [7] V. Cascione, D. Lim, D. Maskell, A. Shea, P. Walker, The response of clay plaster to temperature and RH sinusoidal variations, *MATEC Web Conf.* 282 (2019) 02005, <https://doi.org/10.1051/mateconf/201928202005>.
- [8] A.M. de F. Luiz, S.A.L. Bessa, M.A.P. Rezende, Trends and innovations in earthen plaster mix design: a review, *J. Build. Eng.* 98 (2024) 111346, <https://doi.org/10.1016/j.jobe.2024.111346>.
- [9] T. Santos, L. Nunes, P. Faria, Production of eco-efficient earth-based plasters: influence of composition on physical performance and bio-susceptibility, *J. Clean. Prod.* 167 (2017) 55–67, <https://doi.org/10.1016/j.jclepro.2017.08.131>.
- [10] M.S. Lekshmi, S. Vishnudas, D.G. Nair, Strength, sorptivity and shrinkage characteristics of cow dung stabilized mud mortar, *Mater. Today Proc.* 32 (2020) 782–787, <https://doi.org/10.1016/j.matpr.2020.03.715>.
- [11] T. Ashour, A. Korjenic, A. Abdelfattah, E. Sesto, W. Wu, Shrinkage behavior of stabilized Earth bricks reinforced with wheat and barley straw, *Sustainability* 15 (2023) 16254, <https://doi.org/10.3390/su152316254>.
- [12] A. Laborel-Préneron, J.E. Aubert, C. Magniont, C. Tribout, A. Bertron, Plant aggregates and fibers in earth construction materials: a review, *Constr. Build. Mater.* 111 (2016) 719–734, <https://doi.org/10.1016/j.conbuildmat.2016.02.119>.
- [13] H. Gonzalez-Calderon, G. Araya-Letelier, S. Kunze, C. Burbano-Garcia, Ú. Reidel, C. Sandoval, R. Astroza, F. Bas, Biopolymer-Waste Fiber reinforcement for earthen materials: capillary, mechanical, impact, and abrasion performance, *Polymers* 12 (2020) 1819, <https://doi.org/10.3390/polym12081819>.
- [14] P. Faria, J. Lima, J. Nabais, V. Silva, Assessment of adhesive strength of an earth plaster on different substrates through different methods, in: *5th Historic Mortars Conference HMC2019*, RILEM Publications SARL, Pamploña, Spain, 2019.
- [15] M. Lagouin, J.-E. Aubert, A. Laborel-Préneron, C. Magniont, Influence of chemical, mineralogical and geotechnical characteristics of soil on earthen plaster properties, *Constr. Build. Mater.* 304 (2021) 124339, <https://doi.org/10.1016/j.conbuildmat.2021.124339>.
- [16] K. Stathopoulos, M. Apostolopoulou, A. Bakolas, Enhancement of water resistance of earthen mortars through stabilization, *Constr. Build. Mater.* 289 (2021) 123180, <https://doi.org/10.1016/j.conbuildmat.2021.123180>.
- [17] R.N. Pachamama, P. Faria, M.A.P. Rezende, A. Santos Silva, Effect of cow dung additions on tropical and mediterranean Earth mortars-mechanical performance and water resistance, *Materials* 17 (2024) 2885, <https://doi.org/10.3390/ma17122885>.
- [18] V.E. García-Vera, M. Lanzón, Physical-chemical study, characterisation and use of image analysis to assess the durability of earthen plasters exposed to rain water and acid rain, *Constr. Build. Mater.* 187 (2018) 708–717, <https://doi.org/10.1016/j.conbuildmat.2018.07.235>.
- [19] L. Walter, Y. Estevez, G. Medjigbodo, J.-E. Aubert, L. Linguet, O. Nait-Rabah, Influence of eco-friendly dispersants on the properties of a lateritic soil-based mortar, *Constr. Build. Mater.* 411 (2024) 134307, <https://doi.org/10.1016/j.conbuildmat.2023.134307>.
- [20] J. Delvigne, *Pédogenèse en zone tropicale. La formation des minéraux secondaires en milieu ferrallitique*, *Bull. Mineral.* 88 (1965) 369.
- [21] R.R. Weil, C.B. Nyle, *The Nature and Properties of Soils*, fifteenth ed., Pearson Education Limited, 2016.
- [22] B.L. Allen, B.F. Hajek, Mineral occurrence in soil environments, *Miner. Soil Environ.* (1989) 199–278, <https://doi.org/10.2136/sssabookser1.2ed.c5>.
- [23] DIN 18947, *Earth Plasters - Requirements, Test and Labelling*, 2024.
- [24] M.I. Gomes, P. Faria, T.D. Gonçalves, Earth-based mortars for repair and protection of rammed earth walls. Stabilization with mineral binders and fibers, *J. Clean. Prod.* 172 (2018) 2401–2414, <https://doi.org/10.1016/j.jclepro.2017.11.170>.
- [25] M. Lagouin, A. Laborel-Préneron, C. Magniont, S. Geoffroy, J.-E. Aubert, Effects of organic admixtures on the fresh and mechanical properties of earth-based plasters, *J. Build. Eng.* 41 (2021) 102379, <https://doi.org/10.1016/j.jobe.2021.102379>.
- [26] M.I. Gomes, T.D. Gonçalves, P. Faria, Unstabilized rammed Earth: characterization of material collected from old constructions in south Portugal and comparison to normative requirements, *Int. J. Architect. Herit.* 8 (2014) 185–212, <https://doi.org/10.1080/15583058.2012.683133>.
- [27] R. Delinière, J.E. Aubert, F. Rojat, M. Gasc-Barbier, Physical, mineralogical and mechanical characterization of ready-mixed clay plaster, *Build. Environ.* 80 (2014) 11–17, <https://doi.org/10.1016/j.buildenv.2014.05.012>.
- [28] R.M. Zeh, K.J. Witt, Suction-controlled tensile strength of compacted clays, in: *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering*, IOS Press, 2005, <https://doi.org/10.3233/978-1-61499-656-9-2347>.
- [29] P. Roque, M. Motta, T. de Campos, Suction effects on the tensile strength and unconfined compression of unsaturated soils, *MATEC Web Conf.* 337 (2021) 01016, <https://doi.org/10.1051/mateconf/202133701016>.
- [30] T. Santos, P. Faria, A. Santos Silva, Eco-efficient earth plasters: the effect of sand grading and additions on fresh and mechanical properties, *J. Build. Eng.* 33 (2021) 101591, <https://doi.org/10.1016/j.jobe.2020.101591>.
- [31] L. Randazzo, G. Montana, A. Hein, A. Castiglia, G. Rodonò, D.I. Donato, Moisture absorption, thermal conductivity and noise mitigation of clay based plasters: the influence of mineralogical and textural characteristics, *Appl. Clay Sci.* 132–133 (2016) 498–507, <https://doi.org/10.1016/j.clay.2016.07.021>.
- [32] E. Hamard, J.-C. Morel, F. Salgado, A. Marcom, N. Meunier, A procedure to assess the suitability of plaster to protect vernacular earthen architecture, *J. Cult. Herit.* 14 (2013) 109–115, <https://doi.org/10.1016/j.culher.2012.04.005>.
- [33] J.L. Parracha, A.S. Pereira, R. Velez da Silva, V. Silva, P. Faria, Effect of innovative bioproducts on the performance of bioformulated earthen plasters, *Constr. Build. Mater.* 277 (2021) 122261, <https://doi.org/10.1016/j.conbuildmat.2021.122261>.
- [34] J. Lima, P. Faria, A. Santos Silva, Earth plasters: the influence of clay mineralogy in the plasters' properties, *Int. J. Architect. Herit.* 14 (2020) 948–963, <https://doi.org/10.1080/15583058.2020.1727064>.
- [35] D. César de Mello, T. Osório Ferreira, G. Vieira Veloso, M. Guedes de Lana, F. Alcantara de Oliveira Mello, L. Augusto Di Loreto Di Raimo, C. Ernesto Gonçalves Reynaud Schaefer, M. Rocha Francelino, E.A.M. Inácio Fernandes-Filho, J. Demattê, Pedogenetic processes operating at different intensities inferred by geophysical sensors and machine learning algorithms, *Catena* 216 (2022) 106370, <https://doi.org/10.1016/j.catena.2022.106370>.
- [36] J.C. Ker, *Latossolos do Brasil: uma revisão*, *Geonomos* (1997), <https://doi.org/10.18285/geonomos.v5i1.187>.
- [37] A.P. Chaves, W. Whitaker, Operações de beneficiamento de areia, in: S.L.M. Almeida, A.B. Luz (Eds.), *Manual De Agregados Para a Construção Civil*, CETEM/MCT, Rio de Janeiro, 2009.
- [38] ABNT, NBR 7181: Soils — Granulometric Analysis, 2025.
- [39] ABNT, NBR 17212: Aggregates - Determination of the Unit Weight and air-void Contents, 2025.
- [40] ABNT, 16972, Aggregados - Determinação Da Massa Unitária E Do Índice De Vazios, 2021.
- [41] E. LNEC, 403 – Análise Mineralógica Por Difratometria De Raios X, 1993.
- [42] A. Vaitkus, A. Merkys, S. Gražulis, Validation of the crystallography open database using the crystallographic information framework, *J. Appl. Crystallogr.* 54 (2021) 661–672, <https://doi.org/10.1107/S1600576720016532>.

- [43] M. Quirós, S. Gražulis, S. Girdzijauskaitė, A. Merkys, A. Vaitkus, Using SMILES strings for the description of chemical connectivity in the crystallography open database, *J. Cheminf.* 10 (2018) 23, <https://doi.org/10.1186/s13321-018-0279-6>.
- [44] S. Gražulis, A. Merkys, A. Vaitkus, M. Okulić-Kazarinas, Computing stoichiometric molecular composition from crystal structures, *J. Appl. Crystallogr.* 48 (2015) 85–91, <https://doi.org/10.1107/S1600576714025904>.
- [45] S. Gražulis, A. Daškevič, A. Merkys, D. Chateigner, L. Lutterotti, M. Quirós, N.R. Serebryanaya, P. Moeck, R.T. Downs, A. Le Bail, Crystallography open database (COD): an open-access collection of crystal structures and platform for world-wide collaboration, *Nucleic Acids Res.* 40 (2012) D420–D427, <https://doi.org/10.1093/nar/gkr900>.
- [46] S. Gražulis, D. Chateigner, R.T. Downs, A.F.T. Yokochi, M. Quirós, L. Lutterotti, E. Manakova, J. Butkus, P. Moeck, A. Le Bail, Crystallography open database – an open-access collection of crystal structures, *J. Appl. Crystallogr.* 42 (2009) 726–729, <https://doi.org/10.1107/S0021889809016690>.
- [47] L. Wang, Y. Zhou, W. Shi, Random crowd-induced vibration in footbridge and adaptive control using semi-active TMD including crowd-structure interaction, *Eng. Struct.* 306 (2024) 117839, <https://doi.org/10.1016/j.engstruct.2024.117839>.
- [48] R.T. Downs, M. Hall-Wallace, *The American mineralogist crystal structure database*, *Am. Mineral.* 88 (2003) 247–250.
- [49] A. Merkys, A. Vaitkus, J. Butkus, M. Okulić-Kazarinas, V. Kairys, S. Gražulis, *COD::CIF::Parser*: an error-correcting CIF parser for the Perl language, *J. Appl. Crystallogr.* 49 (2016) 292–301, <https://doi.org/10.1107/S1600576715022396>.
- [50] ABNT, NBR 7215: Portland Cement - Determination of Compressive Strength of Cylindrical Test Specimens, Rio de Janeiro, 2019.
- [51] M.I. Gomes, T.D. Gonçalves, P. Faria, Avaliação da influência do teor de água na trabalhabilidade de argamassas de terra, *Apuntes* 25 (2012) 258–277.
- [52] CEN, EN 1015-3: Methods of Test for Mortar for Masonry – Part 3: Determination of Consistence of Fresh Mortar (By Flow Table), 1999.
- [53] T.Y. Shin, J.H. Kim, First step in modeling the flow table test to characterize the rheology of normally vibrated concrete, *Cement Concr. Res.* 152 (2022) 106678, <https://doi.org/10.1016/j.cemconres.2021.106678>.
- [54] ABNT, NBR 13278: Mortars Applied on Walls and Ceilings - Determination of the Specific Gravity and the Air Entrained Content in the Fresh Stage, 2005. Rio de Janeiro.
- [55] ABNT, NBR 6457: Soils - Preparation of Samples for Compaction Tests, Characterization and Determination of Moisture Content, 2024. Rio de Janeiro.
- [56] A.M. Forster, G.M. Medero, T. Morton, J. Buckman, Traditional cob wall: response to flooding, *Struct. Surv.* 26 (2008) 302–321, <https://doi.org/10.1108/02630800810906557>.
- [57] G. Minke, *Building with Earth*, Birkhäuser Basel, Basel, 2006, <https://doi.org/10.1007/3-7643-7873-5>.
- [58] S. Tamari, Optimum design of the constant-volume gas pycnometer for determining the volume of solid particles, *Meas. Sci. Technol.* 15 (2004) 549–558, <https://doi.org/10.1088/0957-0233/15/3/007>.
- [59] ABNT, NBR 16867: Soil - Determination of the Bulk Density of Undisturbed Samples - Method Using Hydrostatic Weighing, 2020. Rio de Janeiro.
- [60] CEN, EN 1015-10: Methods of Test for Mortar for Masonry - Part 10: Determination of Dry Bulk Density of Hardened Mortar, 2007.
- [61] CEN, EN 1015-11: Methods of Test for Mortar for Masonry - Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar, 2020.
- [62] M.A. García-Pérez, Use and misuse of corrections for multiple testing, *Methods Psychol.* 8 (2023) 100120, <https://doi.org/10.1016/j.metip.2023.100120>.
- [63] W.M. Farias, *Evolutionary Chemical Weathering Processes and their Influence on the hydro-mechanical Behavior of Soils of the Plateau Central Brazilian*, Universidade de Brasília, 2012. Thesis (PhD Geotechnical Engineering).
- [64] S. Cornu, Y. Lucas, E. Lebon, J.P. Ambrosi, F. Luizão, J. Rouiller, M. Bonnay, C. Neal, Evidence of titanium mobility in soil profiles, Manaus, central Amazonia, *Geoderma* 91 (1999) 281–295, [https://doi.org/10.1016/S0016-7061\(99\)00007-5](https://doi.org/10.1016/S0016-7061(99)00007-5).
- [65] Jr.IA. Carvalho, *Influência da mineralogia e da matéria orgânica na agregação, cor e radiometria de solos altamente intemperizados do estado de Minas Gerais*, Universidade Federal de Viçosa, 2000. Thesis (PhD in Soil Science and Plant Nutrition).
- [66] A.V. Inda Junior, E. Klamt, P.C. Nascimento, *Composição da fase sólida mineral do solo*. Fundamentos Da Química Do Solo, third ed., Porto Alegre: Evangraf, 2006.
- [67] R.M. Cornell, U. Schwertmann, *The Iron Oxides*, Wiley, 2003, <https://doi.org/10.1002/3527602097>.
- [68] W.A. Deer, R.A. Howie, J. Zussman, An introduction to the rock-forming minerals, *Mineral. Soc. Great Brit. Ireland* (2013), <https://doi.org/10.1180/DHZ>.
- [69] Y. Tardy, *Petrology of Laterites and Tropical Soils*, Taylor & Francis, 1997.
- [70] J.K. Mitchell, Soga Kenichi, *Fundamentals of Soil Behavior*, third ed., John Wiley & Sons, Inc., New York, 2005.
- [71] J. Perić, R. Krstulović, M. Vućak, Investigation of dehydroxylation of gibbsite into boehmite by DSC analysis, *J. Therm. Anal.* 46 (1996) 1339–1347, <https://doi.org/10.1007/BF01979247>.
- [72] B. Zhu, B. Fang, X. Li, Dehydration reactions and kinetic parameters of gibbsite, *Ceram. Int.* 36 (2010) 2493–2498, <https://doi.org/10.1016/j.ceramint.2010.07.007>.
- [73] P. Ptáček, F. Frajkorová, F. Šoukal, T. Opravil, Kinetics and mechanism of three stages of thermal transformation of kaolinite to metakaolinite, *Powder Technol.* 264 (2014) 439–445, <https://doi.org/10.1016/j.powtec.2014.05.047>.
- [74] P.C. Beuria, S.K. Biswal, B.K. Mishra, G.G. Roy, Study on kinetics of thermal decomposition of low LOI goethetic hematite iron ore, *Int. J. Min. Sci. Technol.* 27 (2017) 1031–1036, <https://doi.org/10.1016/j.ijmst.2017.06.018>.
- [75] M.A. Bouhifd, P. Besson, P. Courtial, C. Gérardin, A. Navrotsky, P. Richet, Thermochemistry and melting properties of basalt, *Contrib. Mineral. Petrol.* 153 (2007) 689–698, <https://doi.org/10.1007/s00410-006-0170-8>.
- [76] M.S. Conconi, M. Morosi, J. Maggi, P.E. Zalba, F. Cravero, N.M. Rendtorff, Thermal behavior (TG-DTA-TMA), sintering and properties of a kaolinitic clay from Buenos Aires Province, Argentina, *Cerâmica* 65 (2019) 227–235, <https://doi.org/10.1590/0366-69132019653742621>.
- [77] E.C. Leong, M. Wijaya, Universal soil shrinkage curve equation, *Geoderma* 237–238 (2015) 78–87, <https://doi.org/10.1016/j.geoderma.2014.08.012>.
- [78] P. Narloch, P. Woyciechowski, Assessing cement stabilized rammed Earth durability in A humid Continental climate, *Buildings* 10 (2020) 26, <https://doi.org/10.3390/buildings10020026>.
- [79] J. Wang, B. Ma, H. Tan, C. Du, Z. Chu, Z. Luo, P. Wang, Hydration and mechanical properties of cement-marble powder system incorporating triisopropanolamine, *Constr. Build. Mater.* 266 (2021), <https://doi.org/10.1016/j.conbuildmat.2020.121068>.
- [80] E. Tertre, S. Savoye, F. Hubert, D. Prêt, T. Dabat, E. Ferrage, Diffusion of water through the dual-porosity swelling clay mineral vermiculite, *Environ. Sci. Technol.* 52 (2018) 1899–1907, <https://doi.org/10.1021/acs.est.7b05343>.
- [81] C. Wang, M. Chen, Y. Wang, Surface flaking mechanism of stone components of ancient building complex in Wudang Mountain, China, *Constr. Build. Mater.* 399 (2023) 132611, <https://doi.org/10.1016/j.conbuildmat.2023.132611>.
- [82] F. Gabibov, The analysis of clay soil shrinkage, *E3S Web Conf.* 371 (2023) 02034, <https://doi.org/10.1051/e3sconf/202337102034>.
- [83] M.A. Es-Soufi, J. Saliba, A. Lafourcade, N. Saiyouri, A comparative study of desiccation-induced shrinkage and cracking behavior of clayey soils from a cracked road, *Case Stud. Constr. Mater.* 23 (2025) e05278, <https://doi.org/10.1016/j.cscm.2025.e05278>.
- [84] R.N. Yong, M. Ohtsubo, Interparticle action and rheology of kaolinite-amorphous iron hydroxide (ferrihydrite) complexes, *Appl. Clay Sci.* 2 (1987) 63–81, [https://doi.org/10.1016/0169-1317\(87\)90014-7](https://doi.org/10.1016/0169-1317(87)90014-7).
- [85] M. Arias, M.T. Barral, F. Diaz-Fierros, Effects of iron and aluminium oxides on the colloidal and surface properties of Kaolin, *Clays Clay Miner.* 43 (1995) 406–416, <https://doi.org/10.1346/CCMN.1995.0430403>.
- [86] Q.-B. Bui, J.-C. Morel, S. Hans, P. Walker, Effect of moisture content on the mechanical characteristics of rammed earth, *Constr. Build. Mater.* 54 (2014) 163–169, <https://doi.org/10.1016/j.conbuildmat.2013.12.067>.
- [87] Hajjar A. El, P. Chauhan, N. Prime, O. Plé, Effect of suction on the mechanical characteristics of uniformly compacted rammed earth, *IOP Conf. Ser. Earth Environ. Sci.* 143 (2018) 012045, <https://doi.org/10.1088/1755-1315/143/1/012045>.
- [88] S. Bouchemella, S. Taibi, Effect of suction on the mechanical behaviour of unsaturated compacted clay–sand mixtures, *Studia Geotechnica Mech.* 44 (2022) 175–189, <https://doi.org/10.2478/sgem-2022-0016>.
- [89] S.M. Rao, *Stabilization of Earthen Building Materials by Select Native Binders*, Springer International Publishing, Cham, 2023, <https://doi.org/10.1007/978-3-031-48987-7>.

- [90] A. Ajaz, R.H.G. Parry, Stress-strain behaviour of two compacted clays in tension and compression, *Geotechnique* 25 (1975) 495–512, <https://doi.org/10.1680/geot.1975.25.3.495>.
- [91] E. Anglade, J.-E. Aubert, A. Sellier, A. Papon, Physical and mechanical properties of clay-sand mixes to assess the performance of earth construction materials, *J. Build. Eng.* 51 (2022) 104229, <https://doi.org/10.1016/j.job.2022.104229>.
- [92] CEN. EN 998-1, Specification for Mortar for Masonry - Part 1: Rendering and Plastering Mortar, 2016.