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Periodica Polytechnica Civil Engineering

Experimental Evaluation of Thermo-mechanical and Hygroscopic Properties in Earth Blocks Reinforced with Date Palm Fibers and Hybrid Stabilizers

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Received: 22 March 2026, Accepted: 17 June 2026, Published online: 28 July 2026

Abstract
Despite the growing use of natural fibers and mineral stabilizers in earth construction, the combined influence of fiber reinforcement and stabilizer type on the thermo-mechanical and hygroscopic behavior of stabilized earth blocks (SEBs) remains insufficiently understood, particularly regarding pore structure evolution and moisture transport mechanisms. This study addresses this gap through a comprehensive experimental investigation. Mixtures incorporated cement (5%, 10%), lime (5%, 10%), and a hybrid stabilizer (5% cement + 5% lime), combined with date palm fibers (DPFs) at 0%, 0.25%, and 0.5%. The experimental program included mechanical characterization (compressive and flexural strength), physical and hygric assessment (total, open, and water-accessible porosity, water absorption, and capillary water uptake), durability-related transport properties (water vapor transmission and water permeability under pressure), as well as complementary non-destructive and thermal analyses using ultrasonic pulse velocity and Hot Disk thermal conductivity measurements. Results showed that DPFs significantly enhanced thermal insulation but increased porosity and permeability due to greater pore interconnectivity. Although fiber incorporation caused a slight reduction in mechanical strength, the 10% cement-stabilized formulation exhibited the best overall performance, combining the highest strength with the lowest water absorption and permeability. The hybrid formulation (5% cement + 5% lime) did not surpass the 10% cement mixture in durability-related indicators; however, it remains a viable compromise by reducing cement content while maintaining acceptable mechanical performance compared with lime-only and unstabilized mixtures. These findings provide valuable guidance for developing sustainable, thermally efficient, and locally sourced earth-based building materials suited to hot and arid regions.
Keywords
stabilized earth blocks (SEBs), date palm fibers (DPFs), hybrid lime–cement stabilization, thermo-mechanical properties, porosity and permeability, hygroscopic behavior

1 Introduction

Earthen construction remains one of the oldest and most widely used building techniques across the globe [1], offering a sustainable and locally available solution for housing, particularly in rural and arid regions [2]. It is estimated that nearly one-third of the world's population lives in structures made from earth [3, 4], underscoring its continued relevance in contemporary construction. Its widespread appeal lies in its low environmental impact, affordability, excellent thermal regulation, and compatibility with local climates and resources [5]. Among the various traditional methods, such as adobe, rammed earth, cob, compressed earth blocks, and stabilized earth blocks (SEBs), the latter have gained significant attention due to their improved strength and durability [6–8]. This interest is part of a broader movement toward low-carbon masonry materials, in which local soils and agricultural by-products are increasingly valorized

Cite this article as: Harrat, Z. R., Ghazoul, T., Chatbi, M., Idder, A., Belhocine, M., Rahmouni, O., Frih, A., Ali, A. M. "Experimental Evaluation of Thermo-mechanical and Hygroscopic Properties in Earth Blocks Reinforced with Date Palm Fibers and Hybrid Stabilizers", Periodica Polytechnica Civil Engineering, 2026. https://doi.org/10.3311/PPci.44078

to reduce the environmental impact of conventional fired clay and cement-based bricks. In this context, Nagaraju and Bahrami [9] showed that rice husk ash combined with waste brick powder can be used to manufacture geopolymer bricks with promising compressive strength, water absorption, and sustainability performance. Similarly, the incorporation of agricultural residues into earth-based materials offers a promising route for developing sustainable masonry units adapted to local resources and climatic conditions.

SEBs are soil-based materials enhanced with stabilizing agents like lime or cement to improve mechanical performance and resistance to moisture-related degradation [10, 11]. More recently, natural fibers, such as those derived from agricultural by-products like date palm waste, have been incorporated into SEBs to improve properties such as crack resistance [12], flexural strength [13], and thermal insulation [14]. However, despite these potential benefits, the inclusion of plant-based fibers introduces new challenges, especially concerning porosity, water absorption, and permeability, which may adversely affect long-term durability [15, 16].

Cement, commonly used at dosages between 3% and 10%, is known to enhance strength and volume stability, particularly in sandy soils [17–19]. Lime, on the other hand, is effective in stabilizing clay-rich soils, typically used in proportions ranging from 4% to 12% [20]. Parallel to these efforts, numerous studies have explored the addition of natural fibers, such as sisal, straw, and date palm, to reduce shrinkage and improve flexural performance and insulation [21–25]. Yet, while these strategies have advanced SEB performance in specific domains, The interaction between fibers and stabilizers, particularly concerning moisture transfer and internal pore structure, remains an area with insufficient research. Only a limited number of studies have addressed this crucial relationship [26, 27].

Most previous research has focused on the individual effects of stabilizers or fibers, often targeting isolated properties such as compressive strength or water absorption [28–32]. Although these findings have expanded the understanding of component-specific behavior, they seldom provide an integrated perspective on how different additives influence interconnected parameters like porosity, thermal conductivity, and permeability. Consequently, the interplay between fiber content, stabilizer type, pore network configuration, and moisture transport remains a critical knowledge gap.

Furthermore, the majority of existing studies have relied on single-type stabilizers, overlooking the potential advantages of hybrid systems, such as lime–cement combinations, which may offer a more balanced improvement in both mechanical and hygric properties. However, the research gap remains clear: the combined effect of hybrid mineral stabilization and natural fiber reinforcement on the overall behavior of stabilized earth blocks (SEBs) is still insufficiently understood. In particular, limited information is available on how mixed lime–cement stabilizers interact with date palm fibers (DPFs) to affect pore structure, water vapor transport, water permeability, and resistance to moisture-related degradation. These aspects are especially important for SEBs intended for hot, arid, saline, or humid environments where durability and moisture transfer are critical concerns.

To bridge this gap, the main objective of the present study is to experimentally evaluate the combined influence of DPFs, cement, lime, and hybrid cement–lime stabilization on the thermo-mechanical and hygric performance of SEBs after 90 days of curing. More specifically, the study investigates how these components collectively affect compressive and flexural strength, thermal conductivity, porosity, water absorption, capillary uptake, water vapor permeability, and water permeability under pressure. By addressing this objective, the present work provides a comprehensive understanding of how natural fibers and hybrid mineral stabilizers interact to influence the overall performance of SEBs.

The core contribution of this work lies in its integrated evaluation of multiple interdependent properties, including mechanical strength, thermal behavior, hygric performance, detailed porosity characterization in its various forms, and permeability mechanisms related to water and water vapor transport. Unlike prior studies that focused on a single property or used isolated formulations, this research investigates eighteen different SEB compositions with varying stabilizer types, namely lime, cement, and lime–cement hybrid systems, and fiber contents of 0%, 0.25%, and 0.5%. This broad experimental matrix enables a holistic assessment of material behavior and supports the identification of mixtures that balance mechanical integrity, low permeability, thermal insulation, and reduced cement use.

To achieve this, eighteen SEB compositions were designed and prepared, followed by laboratory testing under controlled environmental conditions. The experimental program incorporated standardized procedures for mechanical testing (EN 196-1 [33]), water absorption and porosity (BS 3921 [34], EN 1015-7 [35]), capillary action (NFP 10-502 [36]), water vapor transmission (EN ISO 12572 [37]), and water permeability under pressure. Additionally, ultrasonic pulse velocity was employed to estimate the dynamic modulus of elasticity, and a Hot Disk thermal analyzer was used to determine the thermal conductivity of each composition. The findings contribute valuable data for the development of cost-effective, bio-based construction materials tailored for hot, arid, and environmentally sensitive regions. Beyond identifying suitable SEB formulations, the study supports the valorization of agricultural waste, such as DPFs, and encourages the adoption of low-carbon stabilization methods aligned with sustainable, climate-resilient, and resource-efficient construction practices.

2 Methodology for experiments

This section presents the experimental approach used to evaluate the effects of DPFs and mineral stabilizers on the performance of SEB. Eighteen mixtures were prepared using varying proportions of lime, cement, and fibers, then cured for 90 days. Standardized tests were conducted to assess mechanical strength, thermal conductivity, porosity, and permeability, providing a comparative analysis to identify the most effective formulations for enhanced durability and insulation.

2.1 Components employed

The materials selected for this study include natural earth, hydraulic binders (lime and cement), and plant-based reinforcement fibers. These components were chosen based on their local availability, compatibility with sustainable construction practices, and relevance to traditional earthen architecture. Each material was characterized to ensure suitability for use in stabilized earth block production.

Table 1 Chemical composition and selected physical properties of the earth, cement, and lime used in SEB formulations

Chemical compositions (wt%)	Earth	Cement	Lime
SiO_2	30.42	23.8	<2.5
CaO	28.13	68	>83.3
Al_2O_3	2.58	2.3	<1.5
MgO	0.76	0.48	<0.5
F_2O_3	1.27	0.27	<2
K_2O	0.47	0.12	0.51
Na_2O	0.11	0.04	0.4-0.5
SO_3	17.52	0.65	<0.5
TiO_2	0.15	–	–
P_2O_3	0.08	–	–
$CaCO_3$	–	–	<10
CO_2	–	–	<5
LOI	17.33	0.9	–
Physical properties	Earth	Cement	Lime
Absolute density (g/cm^3)	2.7	2.24	3.1
Apparent density (g/cm^3)	1.3	0.72	1.14
Normal consistency	–	69.5	28±3.0
Finesse following Blaine's method (cm^2/g)	–	11663	4300 -5200
Shrinkage at 28 days (µm/m)	–	–	< 1000
Expansion (mm)	–	–	≤ 3.0
Initial setting time (min)	–	80	160 ± 40
Final setting time (min)	–		250 ± 40
Sand equivalent (ES (%)	11.58	–	–
Liquidity limit (%)	19.45	–	–
Limit of plasticity (%)	11.36	–	–
Consistency index (%)	0.92	–	–
Plasticity index (%)	8.09	–	–

2.1.1 Earth

The primary soil used in this study was sourced from Ksar Mougheul, a region in southwestern Algeria, where it is traditionally employed in earthen construction and heritage restoration. The raw earth was crushed, sieved, and stored in paper bags to ensure homogeneity and protection from moisture prior to use.

Chemical analysis (as detailed in Table 1) confirmed the absence of harmful or reactive compounds, supporting the suitability of the soil for stabilized earth block production. Overall, the physical and chemical properties of the earth meet the fundamental criteria for use in structural and thermally efficient earthen materials.

As shown in Table 1, the raw earth from Ksar Mougheul presents a balanced composition of silica (30.42 wt%) and calcium oxide (28.13 wt%), indicating a calcareous-siliceous profile that is favorable for stabilization with both cement and lime. The moderate alumina (2.58 wt%) and low magnesium oxide (0.76 wt%) contents further support its compatibility with hydraulic binders, while the relatively high SO_3 content (17.52 wt%) suggests the presence of naturally occurring sulfates, a characteristic not uncommon in soils from arid regions.

The cement employed, with high CaO content (68 wt%) and fine particle size (Blaine fineness = 11,663 cm^2/g), ensures rapid hydration and early strength gain, while the lime, of high purity (>83 wt% CaO) and moderate fineness (4,300–5,200 cm^2/g), is suitable for slower pozzolanic reactions, dimensional stability, and workability improvement. Physical property measurements confirm that the earth's density (2.7 g/cm^3 absolute) and granular characteristics provide a stable base for block formation, whereas the hydraulic binders contribute varying setting times, shrinkage control, and binding efficiency.

These chemical and physical characteristics confirm that the selected materials meet the essential criteria for stabilized earth block production, particularly in terms of binder compatibility, reactivity, and durability potential. Their suitability is consistent with the region's tradition of earthen construction and aligns with the study's goal of producing sustainable, thermally efficient, and structurally reliable SEBs.

Furthermore, a granulometric analysis, presented in Fig. 1, revealed a well-graded particle size distribution, with a continuous curve approaching the ideal profile for compressed earth blocks. The Modified Proctor test established an optimal water content of 12%, corresponding to a maximum dry density of approximately 2.0 g/cm^3. These characteristics indicate favorable compaction behavior and workability.

2.1.2 Lime

The lime used in this study is a commercially available hydrated lime, produced by BMSD, a manufacturer located in northwestern Algeria. This binder was selected due to its widespread use in the stabilization of clay-rich soils and its compatibility with earthen construction techniques. The physical and chemical properties of the lime, including its high calcium oxide (CaO) content and low levels of impurities, are presented in Table 1. These characteristics confirm its suitability as a stabilizing agent for improving the durability and cohesion of earth-based materials.

2.1.3 Cement

The cement used in this study is a white Portland cement of type CPJ – CEM II/A-L 52.5N (NA 442), selected for

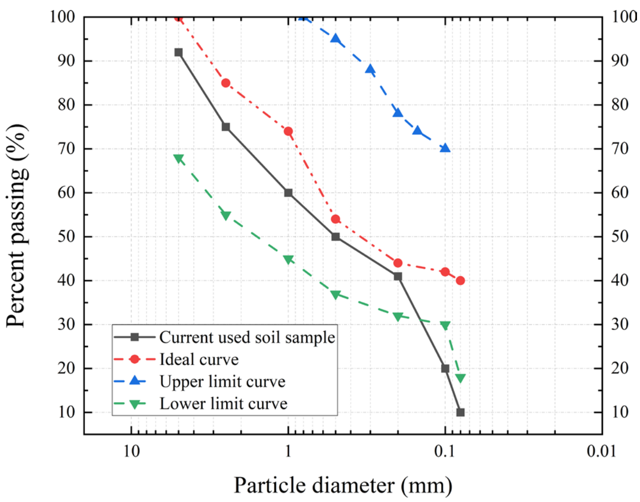

Fig. 1 Particle size distribution curve of the raw earth used in the stabilized earth block formulations

its aesthetic compatibility with the light-colored soil used in heritage restoration projects. The choice of white cement aimed to preserve the architectural appearance of traditional buildings, particularly in the context of restoring historical structures in southern Algeria. The physical and chemical properties of the cement, including its high CaO content and fineness, are detailed in Table 1. These characteristics make it a suitable binder for improving the mechanical performance and durability of SEBs.

2.1.4 Plant fibers

Natural plant fibers extracted from local date palm residues were used as reinforcement in the SEBs. The raw fibers were manually cut into strips approximately 20 mm in length and 3 mm in width. To enhance their compatibility with the soil matrix, the fibers were soaked in water for 24 hours (as illustrated in Fig. 2).

This pre-treatment mainly aimed to remove surface dust and water-soluble impurities, improve fiber wetting, and promote better fiber dispersion and adhesion within the earth matrix [38]. It should be noted that simple water soaking does not significantly remove lignin, which generally requires chemical treatment such as alkaline processing.

The physical and chemical characteristics of the DPFs, including their cellulose content, density, and water absorption capacity, are summarized in Table 2.

2.2 Methods for testing and mix ratios

The experimental matrix consisted of eighteen distinct mixtures prepared to investigate the combined effects of stabilizer type and fiber content on the performance of SEBs. Lime and cement were used individually at two dosage levels 5% and 10% by weight, and also in a hybrid formulation containing 5% lime and 5% cement. A control mixture containing 100% earth without any stabilizer was also included for baseline comparison.

Fig. 2 Preparation and soaking of natural fibers extracted from date palm residues for use in earth block reinforcement

Table 2 Chemical composition and physical properties of DPFs used for reinforcement

Chemical compositions	(wt%)
Cellulose	32 – 35.8
Hemicellulose	24.4 – 28.1
Lignin	26.7 – 28
Fats	7
Physical characteristics	
L (cm)	20
W (cm)	3
T (cm)	0.55
W (%)	53.6
Density (kg/m^3)	720
Expansion (mm)	≤ 3.0
Ab (%)	13.2

Each of the six stabilizer configurations was combined with three levels of DPF reinforcement: 0%, 0.25%, and 0.5% by weight of the dry soil. The complete mix proportions are summarized in Table 3.

Mixing was carried out in a 5-liter capacity laboratory mixer to ensure uniform distribution of components. The fresh mixtures were cast into oiled molds and compacted using a vibrating table for 30 seconds.

Table 3 Mix design proportions of stabilized earth block formulations with varying fiber and stabilizer contents

Mixtures	Earth (%)	Cement (%)	Lime (%)	Fibers (%)	Water (%)
1	100	0	0	0	30
2		5	0		
3		10	0		
4		5	5		
5		0	5		
6		0	10		
7	100	0	0	0.25	30
8		5	0		
9		10	0		
10		5	5		
11		0	5		
12		0	10		
13	100	0	0	0.5	30
14		5	0		
15		10	0		
16		5	5		
17		0	5		
18		0	10		

It should be noted that the specimens were prepared using a laboratory vibration-assisted casting procedure rather than high-pressure mechanical compaction typically employed in industrial stabilized earth block production. Consequently, the obtained density, porosity, and permeability values are representative of vibrated laboratory samples and may differ from those achievable under field or industrial compaction conditions.

After demolding, which occurred 48 hours post-casting, the specimens were air-cured under controlled laboratory conditions (temperature: 21 ± 4°C; relative humidity: 35 ± 5%) for a period of 90 days to allow for full material maturation.

The selected curing conditions were intended to simulate the low-humidity environmental conditions characteristic of hot and arid regions (southern Algeria), where stabilized earth materials are commonly used. However, it should be noted that such relatively dry curing conditions may limit cement hydration and lime pozzolanic reactions, potentially affecting matrix densification, mechanical strength development, and pore structure evolution.

2.3 Tests conducted

A comprehensive series of laboratory tests was performed to evaluate the physical, mechanical, thermal, and permeability-related properties of the SEBs. These tests were selected to assess the influence of both stabilizer type and fiber content on key performance indicators, including strength, porosity, water absorption, and thermal conductivity. Standardized procedures were followed where applicable, ensuring consistency and comparability across all formulations.

2.3.1 Air content

In the fresh state, the stabilized earth block mixture behaves similarly to an earth-based mortar, making it suitable for air content evaluation. The air content was measured in accordance with European Standard EN 1015-7 [35], which is typically applied to mortars. This test was used to estimate the volume of entrapped air within the mix, which plays a critical role in influencing porosity, density, and mechanical performance. The procedure was carried out on freshly prepared mixtures, as illustrated in Fig. 3(a).

2.3.2 Compressive and flexural strength

Mechanical performance was assessed through flexural and compressive strength tests conducted on prismatic specimens measuring 40 × 40 × 160 mm³, following the procedures outlined in European Standard EN 196-1 [33],

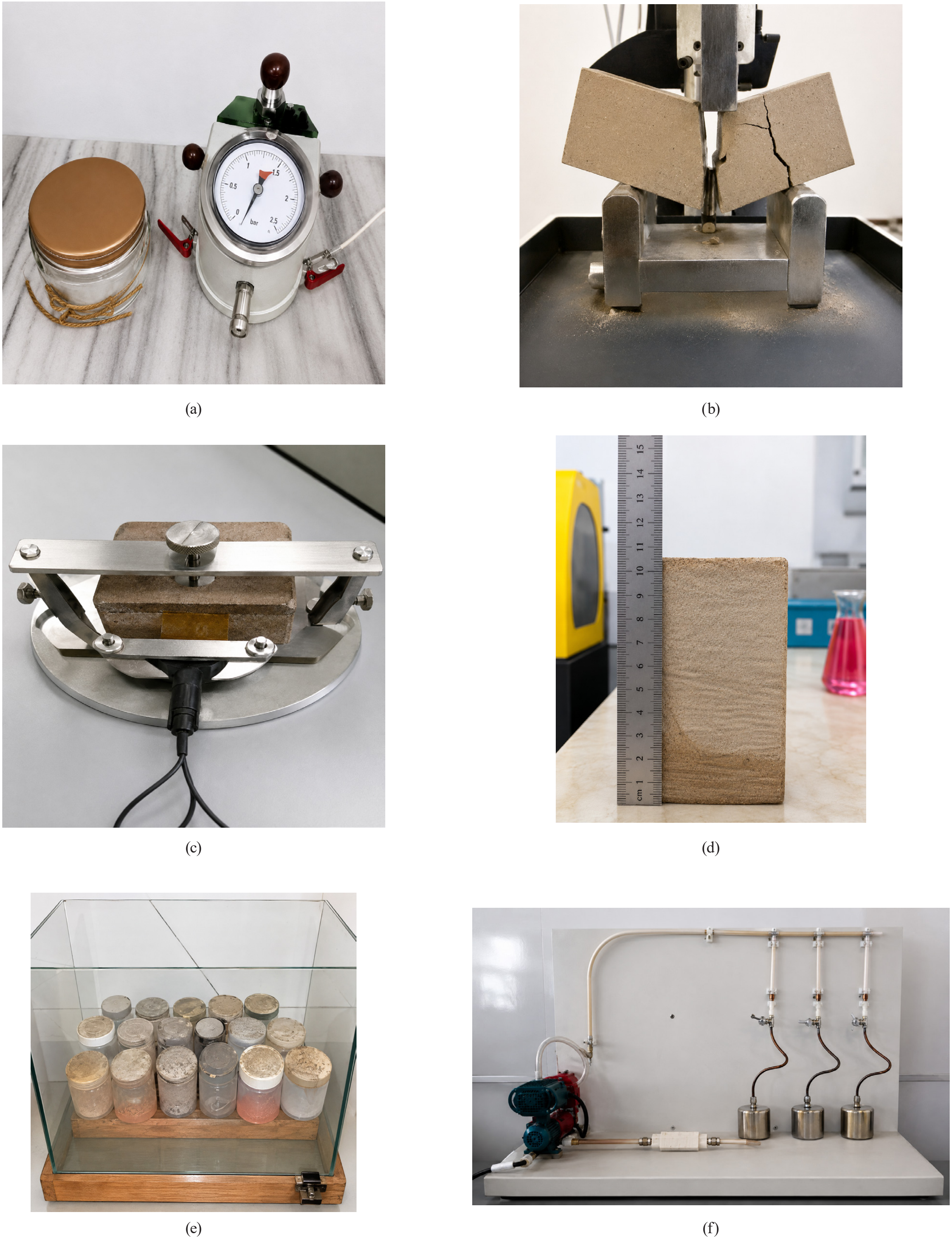

Fig. 3 Overview of experimental procedures conducted on SEBs: (a) air content test; (b) flexural and compressive strength test; (c) thermal conductivity test using Hot Disk; (d) capillary absorption test; (e) water vapor permeability setup; (f) water permeability under pressure

typically used for cementitious mortars. Flexural strength was first determined by applying a three-point bending load at the midpoint of the span. The resulting fractured halves were then subjected to compressive testing to evaluate their compressive strength. These tests were performed using a calibrated testing machine, as illustrated in Fig. 3(b), to ensure consistency across all formulations.

2.3.3 Density

To determine the dry density of the earth blocks, specimens measuring 100 × 100 × 50 mm³ were placed in an oven at 105°C for 24 hours to ensure complete moisture removal. After drying, each sample was weighed (mass *M*) and its volume (*V*) calculated geometrically. The dry density was then obtained by dividing the mass by the volume ($\rho = M / V$), providing insight into the compactness and internal structure of the material.

2.3.4 Total water absorption

The total water absorption (TWA) test was conducted in accordance with British Standard BS 3921 [34]. Stabilized earth block specimens measuring 100 × 100 × 50 mm³ were first oven-dried at 105°C to obtain their dry mass (*Md*), then immersed in water for 24 hours. After immersion, the saturated mass (*Mw*) was recorded. The *TWA*, expressed as a percentage of the dry weight, was calculated using Eq. (1):

$$TWA(\%) = \left(\frac{Mw - Md}{Md}\right) \times 100 . \quad (1)$$

This test provides a measure of the material's capacity to absorb and retain water, which is directly linked to its porosity and durability.

2.3.5 Capillary absorption

Initial water absorption by capillarity was measured in accordance with French Standard NFP 10-502 [36], which is commonly applied to porous construction materials such as limestone and terracotta. The test was conducted on 100 × 100 × 50 mm³ brick specimens. Each specimen was placed in contact with water to a height of 1 cm, and mass gain was recorded at the following time intervals: 0, 15, 30 minutes, and 1, 2, 4, and 8 hours. The capillary absorption behavior was evaluated using two key parameters:

- $\Delta m(t)/S$: The cumulative water uptake per unit surface area (kg/m²), where $\Delta m(t)$ represents the mass of water absorbed at time *t*, and *S* is the surface area of contact between the specimen and water.
- $Z(t)$: The height of the capillary rise (*m*), indicating the vertical penetration depth of water within the material over time.

This test provides valuable insight into the open pore structure and the capacity of the material to draw moisture through capillary action, as illustrated in Fig. 3(d).

2.3.6 Porosity

Porosity plays a critical role in determining the durability, permeability, and mechanical behavior of SEBs. In this study, porosity was evaluated using three complementary methods to capture different aspects of the pore structure. These methods include the estimation of total porosity, water-based volumetric porosity, and open (permeable) porosity. Each approach provides specific insight into the void distribution and connectivity within the material.

The estimation for overall porosity

The total porosity of the earth blocks was estimated using a gravimetric approach based on the ratio between the measured bulk density and the theoretical particle density.

The calculation was performed using Eq. (2):

$$n(\%) = \left(1 - \left(\frac{\rho_{\text{experimental}}}{\rho_{\text{theoretical}}}\right)\right) \times 100 . \quad (2)$$

Where:

- $\rho_{\text{experimental}}$, is the dry bulk density of the block, determined as described in Section 2.3.3.
- $\rho_{\text{theoretical}}$, is the particle density of the solid components, obtained using the pycnometer method.

This method provides an estimate of the overall void volume within the material, encompassing both open and closed pores.

Water's total volume porosity

Water-based volumetric porosity was calculated to estimate the proportion of pore volume accessible to water absorption.

This method, conducted in accordance with British Standard BS 3921 [34], converts *TWA* into porosity using Eq. (3):

$$n(\%) = \frac{(TWA) \times \rho}{100 \times \rho w} . \quad (3)$$

Where:

- *n* (%) is the total porosity based on water volume,
- *TWA* (%) is the total water absorption determined in Section 2.3.4,

- ρ is the dry bulk density of the block (kg/m^3),
- ρw is the density of water, taken as 1000 kg/m^3.

This method provides an indirect yet practical estimate of the pore volume capable of retaining water during immersion, offering insight into the material's absorptive capacity.

Permeable porosity

Permeable, or open, porosity represents the volume of interconnected pores that allow water to flow through the material.

It was calculated based on capillary absorption data using Eq. (4):

$$\varepsilon(\%) = \left(\frac{Vv}{Vt}\right) \times 100\% = \left(\frac{\frac{\Delta m}{S}}{\rho \times Z}\right) \times 100\% . \quad (4)$$

Where:

- ε (%) is the open (permeable) porosity,
- Vv is the volume of absorbed water,
- Vt is the total volume of the capillary-affected region,
- $\Delta m/S$ is the water uptake per unit surface area (kg$\times$m^{-2}),
- ρ is the density of water, taken as 1000 kg/m^3,
- Z is the height of the capillary rise (m).

This method provides insight into the portion of pore volume that contributes to water transport within the material, which is critical for assessing its durability in moisture-prone environments.

2.3.7 Permeability

Permeability is a key indicator of a material's ability to resist water infiltration, which directly affects its long-term durability, especially in humid or aggressive environments. In this study, water permeability under pressure was measured to assess how different stabilizer types and fiber contents influence the water-tightness of SEBs. This test complements the capillary absorption and porosity evaluations by providing insight into the behavior of the material when subjected to direct hydraulic pressure.

Water vapor permeability

Water vapor permeability was evaluated in accordance with EN ISO 12572 [37], using a steady-state method to simulate vapor diffusion through porous materials. The test setup consisted of a cylindrical test specimen with a 90 mm diameter and 20 mm thickness, placed and sealed atop a bottle using wax and silicone to ensure complete insulation along the edges, preventing lateral vapor exchange (Fig. 3(e)).

Inside the sealed bottle, a saturated solution of magnesium chloride ($MgCl_2$) was used to maintain a constant internal relative humidity (HR_1 = 31 ± 2%), while the entire system (bottle + sample) was placed in a controlled glass chamber representing the external environment (HR_2 = 84 ± 3%), regulated by distilled water. This setup established a vapor pressure gradient across the sample to drive diffusion.

The water vapor permeability (δ) was calculated using Eq. (5):

$$\delta = \frac{Gd}{A\Delta P} . \quad (5)$$

Where:

- δ is the water vapor permeability (kg·m^{-1} × s^{-1} × Pa^{-1}),
- G is the mass flow rate of water vapor (kg/s), determined by tracking the change in bottle mass over time (with two measurements per day),
- d is the specimen thickness (m),
- A is the exposed surface area (m^2),
- ΔP is the water vapor pressure difference between the internal and external environments (Pa).

This test provides critical data on the material's breathability and its ability to manage moisture vapor transport, which is essential for applications in variable climate conditions.

Water permeability

The water permeability test was conducted to evaluate the capacity of the material to resist liquid water penetration under hydraulic pressure. The experiment involved applying water pressure directly to the surface of 100 × 100 × 100 mm^3 stabilized specimens.

To guide the flow and ensure watertight conditions, a plastic ring was placed on the upper surface of the specimen and sealed using silicone adhesive. A rubber layer was placed underneath the specimen to prevent leakage at the base (Fig. 3(f)). A hydrostatic pressure of 1 bar was applied to the top surface using a setup inspired by the system described by Bella et al. [38].

The flow rate was determined by measuring the time required to fill a calibrated container, allowing the calculation of the water permeability coefficient (Kw) using Eq. (6):

$$Kw = \frac{QL}{A\Delta P} . \quad (6)$$

Where:

- Kw is the water permeability coefficient (m/s),
- Q is the volumetric flow rate (m^3/s),

- L is the specimen thickness (m),
- A is the surface area subjected to water pressure (m^2),
- ΔP is the applied water pressure (Pa).

This test offers direct insight into the material's permeability under pressure, which complements the capillarity and porosity measurements in assessing overall moisture durability.

2.3.8. Dynamic modulus of elasticity

The dynamic modulus of elasticity (*Ed*) was determined using the ultrasonic pulse velocity (UPV) method, based on wave transmission through the material. This non-destructive technique is widely used to evaluate the mechanical integrity of concrete-like materials. The velocity of wave propagation depends on the material's stiffness and density, offering an indirect yet reliable measure of its elastic behavior [39].

The dynamic modulus was calculated using Eq. (7):

$$Ed = \left(\frac{L^2}{t^2}\right)\left(\rho\frac{(1+v)(1-2v)}{1-v}\right). \tag{7}$$

Where:

- Ed is the dynamic modulus of elasticity (MPa),
- L is the distance between the two ultrasonic transducers (m),
- t refers to the ultrasonic pulse travel time (s),
- ρ is the density of the earth block (kg/m^3),
- v refers to the Poisson's ratio, assumed to be 0.30 for low-strength concrete.

This test provides insight into the material's stiffness and structural integrity without causing damage to the sample, making it particularly suitable for comparative analysis across various stabilized compositions.

2.3.9 Tests of thermal conductivity

Thermal conductivity is a key parameter that reflects a material's ability to conduct heat and is influenced by both its density and moisture content [40]. In this study, thermal conductivity was measured to assess the insulating performance of SEBs, which is particularly relevant for construction in hot and arid climates.

The test was conducted in the energy laboratory using a Hot Disk thermal analyzer (Fig. 3(c)). The device was calibrated prior to testing to ensure measurement accuracy and data reliability. This method allows for transient plane source (TPS) measurements, which are well-suited for evaluating thermal properties of heterogeneous materials like fiber-reinforced earth blocks. By capturing the rate at which heat propagates through the specimen, the thermal conductivity test provides valuable insight into the energy efficiency potential of each formulation.

3 Results and interpretation

This section presents and analyzes the experimental results obtained from the different tests conducted on the SEBs. The influence of stabilizer type (lime, cement, and hybrid) and fiber content (0%, 0.25%, and 0.5%) on the physical, mechanical, thermal, and permeability-related properties is examined. Each parameter is discussed in relation to its impact on durability, strength, and insulation performance. The results provide comparative insights into the effectiveness of the different formulations and help identify optimal combinations for sustainable and high-performance earth-based construction materials.

3.1 Air content

The air content test was conducted to quantify the initial porosity in the fresh state of the stabilized earth mixtures, which reflects the volume of entrapped air resulting from mixing and material interaction. This primary porosity, often formed by spherical air voids, significantly influences the compaction, workability, and eventual performance of the hardened material.

As shown in Fig. 4, the results indicate that air content generally increased with the addition of either stabilizers or plant fibers. The inclusion of cement or lime contributed to a slight stiffening of the mix, reducing flowability and trapping more air during mixing. Moreover, fibers introduced further complexity into the internal structure. Their irregular

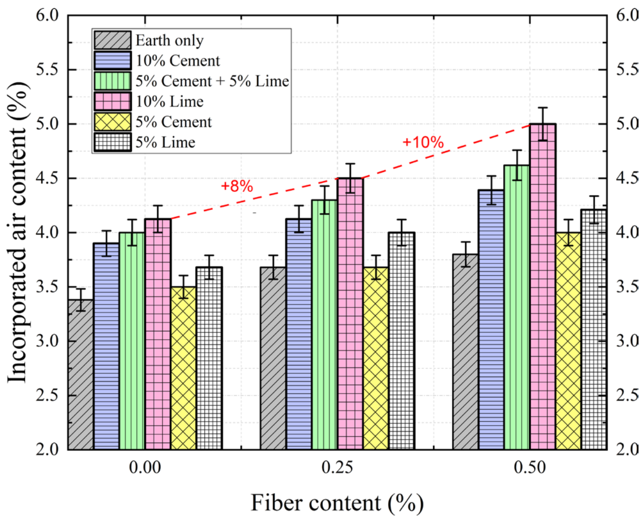

Fig. 4 Air content values of stabilized earth block compositions with varying fiber and stabilizer dosages

geometry and tendency to interlock created micro-zones that favored air entrapment. Interestingly, the addition of fibers, particularly at higher contents, also impeded the upward movement of air bubbles, preventing them from escaping to the surface before setting. This phenomenon resulted in a higher volume of retained voids in the fresh mix. However, while this could suggest increased porosity, it does not necessarily translate to poor material quality. In fact, the distribution and size of these voids may contribute positively to thermal insulation and vapor diffusion, depending on their connectivity and stability after curing.

3.2 Flexural and compressive strength

Mechanical strength is a key indicator of brick durability and wall rigidity, with compressive strength strongly influenced by the porosity of the material [41]. As shown in Table 4, increasing the stabilizer content significantly improved compressive strength, with values ranging from 0.8 to 2.5 MPa. This improvement is attributed to enhanced hydration and the formation of cementitious compounds that contribute to a denser, stronger matrix [42].

However, the addition of fibers (0.25–0.5%) resulted in a noticeable reduction in compressive strength across all formulations. This can be explained by two main factors: (1) the elastic, flexible nature of fibers that alters the load-bearing behavior of the mix [16], and (2) increased air voids introduced by fibers, as previously confirmed in the air content test. This behavior may be associated with increased void content and weaker fiber–matrix interaction zones, which can reduce the efficiency of stress transfer within the stabilized matrix.

In terms of flexural strength, the best performance was recorded for the mix containing 10% cement and 0% fibers (1.02 MPa), while the lowest (0.21 MPa) was observed in the unstabilized earth with 0.5% fiber. The slight reduction in flexural strength with fiber addition is likely due to fiber-matrix interface issues, such as poor fiber dispersion, sliding effects, or suboptimal fiber length and content [22]. Moreover, excess fiber may hinder effective stress transfer by reducing contact with the cementitious matrix [21].

These trends align with findings in the literature, where natural fibers improve crack resistance and reduce shrinkage, but may compromise compressive and flexural strength when not well integrated [43].

3.3 Dry block density

Dry density is a key physical property that reflects the internal compactness of the material and is influenced by various factors including mix composition, curing conditions, and stabilization method [44]. As shown in Table 4, the density values of the tested blocks ranged from 1120 to 1437 kg/m^3, which are considered moderate due to the absence of mechanical compaction, only chemical stabilization was applied.

A slight decrease in density was observed with the addition of fibers. This reduction can be attributed to the increased internal voids introduced by the fibrous network. Additionally, the low specific weight of the fibers may have partially replaced heavier mineral components (such as earth or stabilizers), contributing further to the drop in overall density.

Table 4 Experimental results of physical, mechanical, and hygric properties of stabilized earth block compositions

Mixtures	5% Cement			10% Cement			5% Lime		
Fibers (%)	0	0.25	0.5	0	0.25	0.5	0	0.25	0.5
Compressive strength (MPa)	1.61	1.54	1.42	2.50	2.43	2.31	1.14	1.10	0.98
Flexural strength (MPa)	0.61	0.59	0.55	1.02	0.99	0.96	0.36	0.35	0.32
Bulk density (Kg/ m^3)	1350	1337	1315	1437	1423	1412	1207	1182	1175
Total absorption (%)	13.52	13.72	14.7	10.2	10.56	10.78	16.37	17.42	19.61
Initial absorption (Kg × m^{-2} × h$^{-1/2}$)	5.86	6.68	7.11	3.18	3.38	3.76	8.75	10.13	11.00
Mixtures	10% Lime			5% Lime + 5% Cement			Earth only		
Fibers (%)	0	0.25	0.5	0	0.25	0.5	0	0.25	0.5
Compressive strength (MPa)	1.69	1.59	1.50	2.07	1.98	1.90	1.09	0.93	0.80
Flexural strength (MPa)	0.60	0.57	0.54	0.88	0.86	0.82	0.24	0.22	0.21
Bulk density (Kg/ m^3)	1267	1259	1245	1382	1365	1345	1152	1144	1120
Total absorption (%)	14.20	14.42	15.69	10.58	11.10	12.58	/	/	/
Initial absorption (Kg × m^{-2} × h$^{-1/2}$)	7.13	8.02	8.92	4.82	5.44	5.84	/	/	/

3.4 Total water absorption

The TWA provides valuable insight into the overall porosity of the material, particularly the volume of voids accessible to liquid water when the block is immersed. In general, lower water absorption is associated with higher durability and greater resistance to moisture-related degradation [45].

As shown in Table 4, water absorption increased proportionally with the addition of plant fibers. Fiber-free specimens absorbed significantly less water than those containing fibers. This increase can be attributed to two main factors: (1) the inherent hydrophilic and porous nature of DPFs, which tend to absorb and retain water [21], and (2) the heterogeneous interface between the fibers and the matrix, which may lead to localized voids and microchannels that facilitate water ingress.

Conversely, increasing the stabilizer content, particularly cement, led to a reduction in TWA. The lowest absorption value was recorded for the 10% cement, 0% fiber mix (10.2%), while the highest was observed in the 5% lime, 0.5% fiber mix (19.61%). These values remain within acceptable ranges when compared to conventional materials, such as concrete blocks (4–25%) and clay bricks (0–30%) [46].

3.5 Capillary absorption

Capillary absorption reflects the ability of porous materials to draw water through suction forces, which directly relates to the size and connectivity of their pore structure. As illustrated in Fig. 5, the absorption curves follow a two-phase behavior commonly observed in porous building materials.

The first phase, occurring between 0 and 30 minutes, corresponds to the rapid saturation of macropores, and its slope is largely influenced by the type and content of the stabilizer used. During this phase, materials with larger or more open pore networks exhibit faster water uptake.

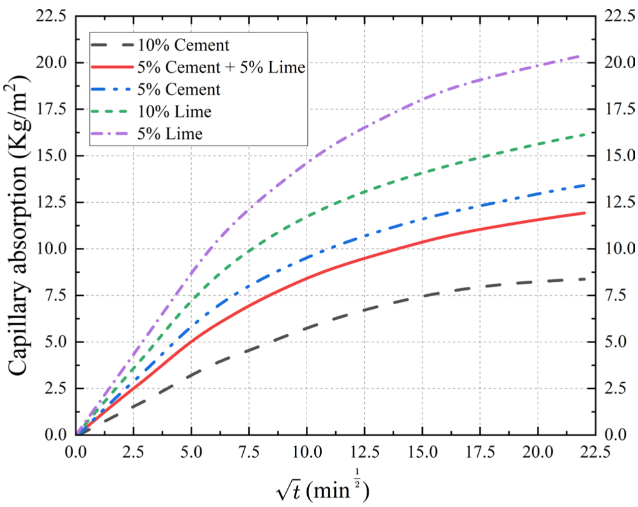

Fig. 5 Capillary water absorption behavior of SEBs containing 0.25% DPF, plotted as a function of the square root of time

The second phase, beyond 30 minutes, represents the continued capillary rise into mesopores and micropores, a process referred to as sorptivity. This stage progresses more slowly as water penetrates finer pore structures.

Table 4 shows that the inclusion of fibers led to an increase in initial water absorption. The highest value, recorded at 11 kg/m^2, was observed for the composition containing 5% lime and 0.5% fiber, while the lowest value of 3.18 kg/m^2 corresponded to the mixture with 10% cement and no fiber. These results indicate that cement-stabilized blocks demonstrate greater resistance to capillary water ingress compared to those stabilized with lime, especially when no fibers are added.

The observed trends confirm that fiber addition increases capillary absorption, likely due to the porous and hydrophilic nature of the fibers and the voids they introduce. However, this effect can be mitigated through optimal stabilization, particularly with cement-based formulations.

3.6 Porosity

Porosity plays a central role in influencing the mechanical, thermal, and hygric behavior of SEBs. Previous research has shown that the inclusion of natural fibers like sisal can reduce porosity in certain cases, with values dropping from 33% to 29% as fiber content increased up to 0.75% [47]. Bogas et al. [6] reported total porosity values of 34.7% for unstabilized blocks, 29.9% for blocks stabilized with 8% cement, and 32.9% for a hybrid composition of 4% lime and 4% cement. Other studies have shown total porosity values ranging between 15% and 25% with cement dosages between 3% and 11% [48].

In this study, as presented in Table 5 and illustrated in Fig. 6, the total porosity ranged from 22.99% to 36.74%, increasing with the addition of DPFs. This rise in porosity is attributed to the fibrous structure and the additional voids created at the fiber–matrix interface. Conversely, increasing stabilizer content, particularly cement, resulted in a notable reduction in porosity. This effect may be associated with improved matrix compactness and partial pore refinement resulting from cement hydration [49].

The water-based volume porosity, which measures pores accessible to water during immersion, ranged from 15.82% to 28.54%, lower than total porosity values. This indicates that a portion of the voids are either closed or not immediately accessible to water within a 24-hour period.

Table 5 Total, volumetric, and open porosity values of stabilized earth block compositions

Mixtures	Fibers (%)	Estimate of total porosity (%)	Total volume porosity in water (%)	Open porosity (%)
5% Cement	0	26.03	20.13	18.90
	0.25	27.06	21.05	20.88
	0.5	28.45	23.15	21.55
10% Cement	0	22.99	15.82	14.45
	0.25	23.90	16.61	15.36
	0.5	24.57	18.37	17.09
5% Lime	0	32.76	25.92	24.99
	0.25	34.22	27.76	27.30
	0.5	34.76	28.54	28.21
10% Lime	0	28.94	24.08	21.61
	0.25	29.47	24.91	23.59
	0.5	30.45	25.59	25.49
5% Lime + 5% Cement	0	24.07	17.83	17.21
	0.25	25.08	19.51	18.76
	0.5	26.30	20.47	19.47
Earth only	0	26.03	20.13	18.90
	0.25	27.06	21.05	20.88
	0.5	28.45	23.15	21.55

Open porosity, representing the volume of interconnected pores allowing fluid transport, varied between 14.45% and 28.21%. The proportion of open pores relative to total porosity ranged from 68.81% to 84.53%, confirming that a large fraction of voids is readily permeable under normal conditions.

Furthermore, capillary-active pores were found to dominate the porous network of SEBs. The proportion of interconnected pores that absorbed water during the capillary test ranged between 91.37% and 99.59%, reinforcing the observation that most open pores in the material are connected and active during short-term water exposure.

In addition to the influence of fibers and compaction conditions, the relatively dry curing environment may have contributed to the higher open porosity values observed in certain mixtures, particularly those containing lime and fibers. Limited moisture availability during curing can restrict hydration and pozzolanic reactions, resulting in a less dense pore structure and increased pore connectivity.

These results demonstrate that fiber inclusion increases porosity and void connectivity, while cement-based stabilization effectively densifies the matrix and reduces both total and open porosity. The data highlight the importance of balancing fiber content and stabilizer dosage to optimize durability and hygric performance in SEB applications.

3.7 Permeability

Permeability is a critical parameter influencing the long-term durability and resistance of SEBs to environmental degradation. It reflects the ability of the material to resist fluid transport, whether in the form of liquid water, vapor, or dissolved salts, through its porous network.

Previous studies have demonstrated that increasing cement content significantly reduces water permeability in earthen materials. For instance, Bahar et al. [41] reported a drop in permeability from 14×10^{-8} to 0.27×10^{-8} m/s when cement content was increased from 5% to 20% using the constant head method. Similarly, Bogas et al. [6] observed permeability values of 3.21×10^{-7} and 9.82×10^{-7} m/s for compositions stabilized with 8% cement and a 4% lime + 4% cement hybrid, respectively.

In terms of water vapor transport, permeability values ranging between 3×10^{-12} and 13×10^{-12} kg/(m·s·Pa) have been reported for various earth-based materials, underscoring their semi-permeable and breathable nature.

In this study, the permeability of SEBs was assessed through multiple experimental setups after 90 days of curing, including water permeability under pressure, and water

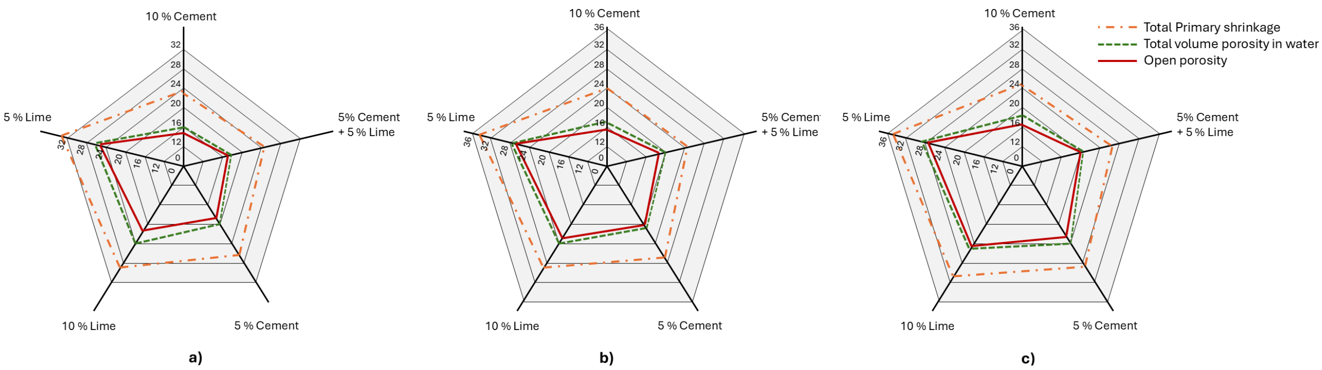

Fig. 6 Variation of total porosity in SEBs as a function of stabilizer type and dosage: (a) 0% Fiber content; (b) 0.25% Fiber content; (c) 0.5% Fiber content

vapor permeability. The results, detailed in the following subsections, provide a comprehensive evaluation of how different stabilizer and fiber combinations influence fluid transport behavior in SEBs.

3.7.1 Water vapor permeability

Water vapor permeability is essential for evaluating the breathability of building materials, as it influences the ability of walls to release moisture and prevent condensation-related damage.

In this study, results depicted in Fig. 7, showed that water vapor permeability increased with fiber content, with the highest value recorded in unstabilized blocks containing 0.5% fiber. This is likely due to the porous and hydrophilic nature of natural fibers, which enhance vapor transport within the matrix. Conversely, the lowest permeability was observed in the composition containing 10% cement and no fibers, highlighting the effect of cement in densifying the structure and restricting vapor movement. In general, non-SEBs exhibited higher vapor permeability, favoring rapid drying, while increased stabilizer content reduced permeability, with cement proving more effective than lime in limiting vapor diffusion.

3.7.2 Water permeability

The effect of fiber inclusion on water permeability was assessed to understand how natural reinforcement impacts the material's ability to resist water infiltration under pressure. As shown in Fig. 8, permeability values ranged from 14.2×10^{-7} to 28.3×10^{-7} m/s, indicating moderate permeability across all compositions.

The addition of fibers, particularly at 0.25% and 0.5%; resulted in a noticeable increase in water permeability.

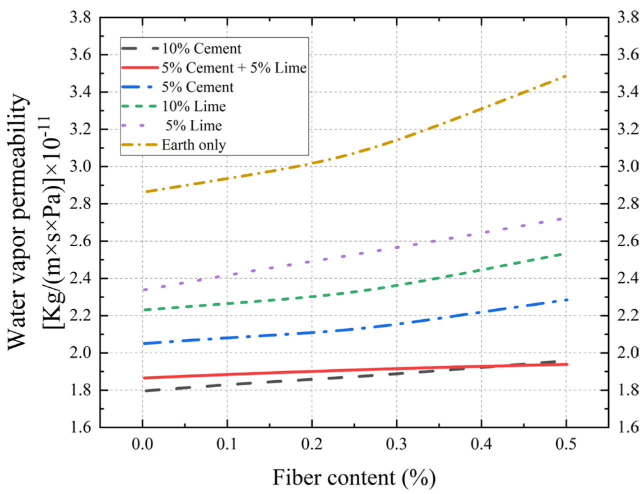

Fig. 7 Water vapor permeability of stabilized earth block compositions with varying fiber and stabilizer contents

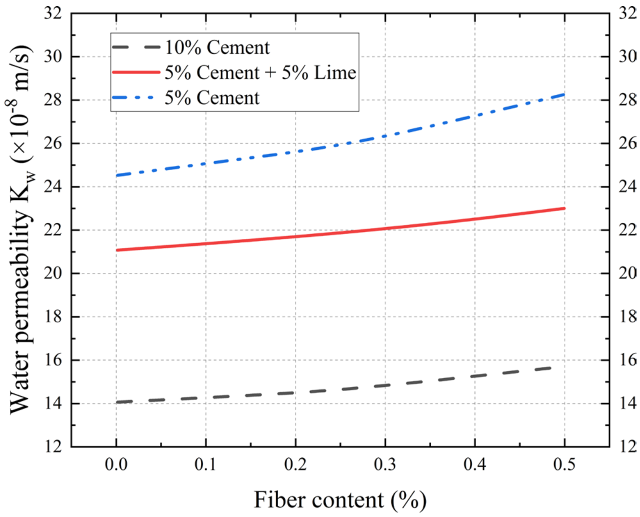

Fig. 8 Water permeability of SEBs as influenced by fiber content and stabilizer type

This effect may be related to increased pore connectivity and the possible formation of preferential flow paths around the fiber–matrix interface. Compared to fiber-free specimens, the presence of fibers increased the permeability by up to 7%, with the hybrid composition (5% cement + 5% lime) showing an even greater increase of 11.5%. This suggests that fiber-induced voids and weak interfaces can contribute to a more open and continuous porous network, facilitating water flow. Although the hybrid 5% cement + 5% lime formulation showed a higher relative increase in water permeability when fibers were incorporated, it should not be interpreted as the most durable mixture. The 10% cement-stabilized formulation exhibited the most favorable overall performance, combining higher strength, lower water absorption, lower porosity, and reduced permeability. This confirms the effectiveness of cement stabilization in limiting water ingress, probably through improved matrix compactness and reduced pore connectivity. Nevertheless, the hybrid formulation remains of interest from a sustainability perspective because it partially reduces cement consumption while maintaining better mechanical performance than lime-only and unstabilized mixtures. Therefore, the hybrid mixture should be considered a compromise solution rather than the optimum durability formulation. Some stabilized compositions also showed water seepage during the test, which may be related to insufficient compaction or heterogeneous fiber dispersion.

The relationship between open porosity and water permeability in cement-stabilized samples was further analyzed (Fig. 9). A strong positive correlation was observed: higher porosity levels led to increased permeability, largely due to changes in pore shape, connectivity, and geometry. In contrast, capillary pores formed in mixes

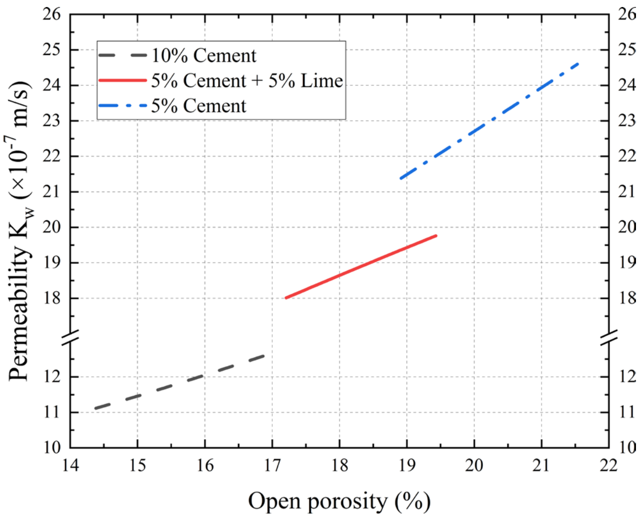

Fig. 9 Correlation between open porosity and water permeability in SEBs

with a low water-to-binder (W/B) ratio were smaller and less connected, resulting in reduced permeability.

3.8 Elastic variable modulus

The dynamic modulus of elasticity (Ed) provides a preliminary assessment of a material's stiffness and is often correlated with its porosity and mechanical integrity. This test offers valuable insight into the material's behavior under dynamic or vibrational loads and can serve as a non-destructive indicator of internal defects or weak zones.

As illustrated in Fig. 10, the modulus of elasticity values for the tested SEB compositions ranged from 1.68 to 5.57 GPa. The highest values were recorded in compositions with higher cement content, while the lowest were observed in lime-stabilized and fiber-rich mixes.

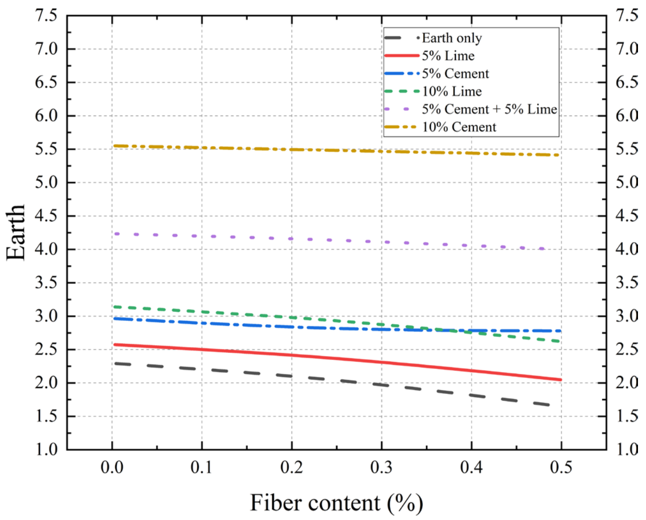

Fig. 10 Dynamic modulus of elasticity of SEBs as a function of fiber content and stabilizer type

The inclusion of DPFs was found to reduce the modulus of elasticity, which is attributed to the creation of voids around the fiber–matrix interface and the increase in overall porosity. These voids disrupt the continuity of the load-bearing matrix and lower the stiffness of the material.

Conversely, increasing the quantity of mineral stabilizers, particularly cement, significantly improved the elastic modulus. Cement enhanced matrix cohesion and reduced porosity, resulting in stiffer and more compact structures. Lime-stabilized samples, on the other hand, showed the lowest elastic modulus values, reflecting their more fragile and less cohesive microstructure under dynamic loading conditions.

3.9 Thermal conductivity

Thermal conductivity is a key indicator of a material's insulation capacity and energy efficiency. As shown in Fig. 11, a noticeable reduction in thermal conductivity was observed with the incorporation of DPFs, especially in unstabilized compositions.

The most significant drop of 16.28% was recorded in the mix containing 0.5% fiber and no stabilizer, demonstrating the impact of natural fibers on enhancing thermal insulation. In contrast, compositions containing 10% cement and 0.25% fiber exhibited only a minor decrease in conductivity. This suggests that while fiber inclusion promotes insulation, the densifying effect of cement can partially counteract the thermal benefits introduced by the fibers.

The improved insulating behavior of fiber-reinforced samples is partly due to faster drying and water loss, which replaces absorbed water (a better conductor) with air (a poor conductor) [50]. Additionally, the decline in thermal

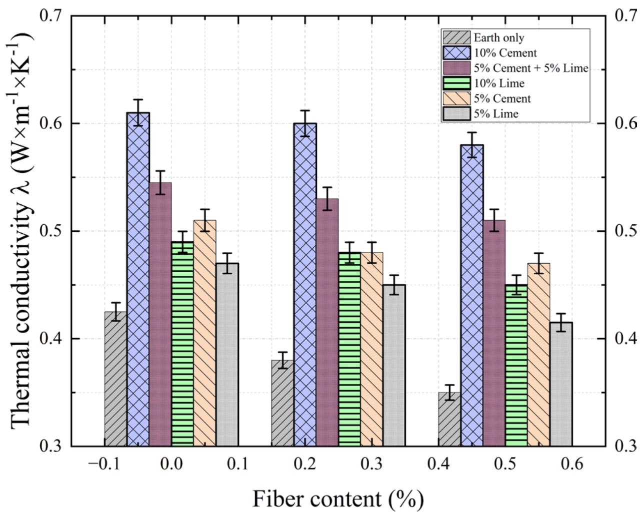

Fig. 11 Thermal conductivity of SEBs with varying fiber contents and stabilizer combinations

conductivity can be attributed to the increased porosity, reduced density, and matrix heterogeneity caused by the fiber network. These factors disrupt the continuity of heat transfer pathways within the material.

4 Conclusion

This study investigated the combined effects of hybrid lime–cement stabilization and date palm fiber reinforcement on the thermo-mechanical, hygric, and durability-related properties of stabilized earth blocks (SEBs). A comprehensive experimental program was conducted on 18 compositions, varying both stabilizer and fiber content, to evaluate fresh-state properties, mechanical performance, porosity characteristics, permeability, and thermal behavior. Key findings can be summarized as follows:

- Air Content: Increased with the addition of both fibers and stabilizers due to entrapped voids and hindered air escape, highlighting the need for optimal mixing to minimize early-stage porosity.
- Mechanical Strength: Compressive strength improved with higher stabilizer content, especially cement, reaching up to 2.5 MPa. However, fiber addition slightly reduced compressive and flexural strength due to void formation and elastic behavior. The highest flexural strength (1.02 MPa) was achieved with 10% cement and no fiber.
- Dry Density: Values ranged from 1120 to 1437 kg/m^3. Fiber inclusion slightly decreased density, while stabilization increased it, indicating improved compaction and matrix continuity.
- Water Absorption: Total water absorption increased with fiber content and decreased with higher stabilizer dosages. The most absorbent composition (19.61%) included 5% lime and 0.5% fiber, while the least absorbent (10.2%) was 10% cement without fiber.
- Capillary Absorption: Initial water uptake was highest in fiber-rich, lime-stabilized blocks and lowest in cement-stabilized compositions. Two distinct absorption stages, macropore filling and sorptivity; were clearly observed.
- Porosity: Total porosity ranged from 22.99% to 36.74%, increasing with fiber content. Cement-based stabilization effectively reduced porosity, while open porosity showed strong correlation with water permeability. Capillary-active pores dominated, with 91–99% of pores participating in short-term absorption.
- Water Vapor Permeability: Fiber addition increased vapor permeability, while stabilizers, particularly cement, reduced it. Cement-stabilized samples showed better moisture resistance, whereas unstabilized samples were more breathable.
- Water Permeability: Increased with fiber addition due to better pore connectivity and matrix disruption. The hybrid composition (5% lime+5% cement) showed the highest permeability rise (11.5%), while 10% cement maintained the best resistance to water flow.
- Dynamic Modulus of Elasticity: Values ranged from 1.68 to 5.57 GPa. Fiber addition reduced elasticity due to increased porosity, while cement significantly improved stiffness. Lime-stabilized samples exhibited the lowest values due to weaker structural cohesion.
- Thermal Conductivity: Fiber-rich mixes exhibited up to 16.28% lower conductivity, improving thermal insulation. The reduction is attributed to increased porosity, lower density, and the replacement of water with air during drying. Cement partially offset this benefit by densifying the matrix.

This study has some limitations that should be acknowledged. First, the specimens were prepared using laboratory vibration rather than high-pressure mechanical compaction; therefore, the reported density, porosity, and permeability values should be interpreted within this preparation context. Second, the relatively dry curing condition may have limited cement hydration and lime pozzolanic reactions, which could have influenced strength development and pore structure. Third, the proposed explanations related to pore refinement, matrix cohesion, and fiber–matrix interaction are based on macroscopic observations and require future validation using microstructural techniques such as SEM, XRD, or MIP. In addition, the long-term durability of untreated date palm fibers against moisture absorption, biodegradation, fungal attack, and alkali-induced deterioration was not assessed. Future work should therefore investigate the effects of compaction pressure, controlled curing humidity, fiber chemical treatment, microstructural evolution, and long-term durability under realistic environmental exposure conditions.

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