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Research Article

Artisanal lime as a low-carbon stabilizer for enhanced stabilized earth blocks in sustainable earthen structure rehabilitation

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Abstract

This study investigates artisanal lime as a low-carbon stabilizer for stabilized earth blocks (SEBs) to optimize the sustainable rehabilitation of earthen structures while reducing cement use. Conducted in Mougheul, Bechar region, Algeria, the study adopts a circular economy approach by valorizing local soil and traditionally produced lime, minimizing cement's environmental impact. A mixed stabilization method (cement/artisanal lime) was tested at replacement rates of 0%, 12.5%, 25%, 50%, and 100%. Physico-mechanical properties, including density, water absorption, porosity, and compressive/flexural strengths, were evaluated at 28 and 90 days per international standards. At 12.5% replacement, SEBs achieve a compressive strength of 1.94 MPa at 28 days, a water absorption reduction of 1.96%, and a porosity decrease of 2.83% at 90 days, enhancing the stability of the earthen material and complying with international standards. Compared to industrial lime, artisanal lime offers comparable performance with reduced environmental impact. These findings support heritage preservation and Sustainable Development Goals (SDGs) through low-emission construction. Future research should explore long-term material stability and bio-based stabilizers.

1. Introduction

Earth has been a cornerstone of construction for millennia, prized for its availability and adaptability [1]. However, modern construction techniques, particularly those reliant on cement, have largely replaced earth-based methods, contributing significantly to environmental degradation. The building sector accounts for 39% of global CO_2 emissions, with cement production responsible for 8% [2]. These energy-intensive materials also deplete natural resources and inflate construction costs, which can represent up to 70% of housing expenses in developing regions [3]. In response, raw earth has garnered renewed interest as a sustainable building material due to its abundance, local availability, low cost, renewability, and eco-friendly properties [4-6]. Over half the global population resides in earthen housing, particularly in developing countries where demand for affordable, sustainable materials is critical [7,8,9]. Yet, the material's susceptibility to water and low mechanical strength limits its widespread adoption, necessitating innovative stabilization methods to enhance earthen material stability while prioritizing sustainability [10,11].

The rehabilitation of earthen structures represents a critical challenge in heritage conservation, requiring materials that maintain structural integrity while preserving cultural authenticity and minimizing environmental impact [12]. Traditional earth construction often employs vegetable or

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mineral additives to improve durability and performance [13-15]. Stabilization techniques include chemical, mechanical, and physical methods, with chemical stabilization being the most prevalent due to its irreversible effects and enhanced water resistance [16,17]. Cement, a widely used chemical stabilizer, significantly improves earthen material stability but exacerbates environmental concerns, contributing approximately 5% to global CO_2 emissions [18]. Consequently, researchers have explored alternative stabilizers to reduce cement reliance and mitigate environmental impact [19]. Pozzolanic materials and industrial by-products, such as lime, fly ash, or slag, offer viable options for stabilizing earth, leveraging local resources to enhance sustainability [20-22]. In southern Algeria, particularly in the arid, high-temperature region of Mougheul, Bechar, local resources like artisanal lime present opportunities for valorization as low-carbon stabilizers [23].

Previous studies have shown that lime stabilization is particularly effective for clayey soils, requiring a dosage of 4–12%, compared to cement's 2.5–10% for sandy soils [8,18,24]. However, excessive cement dosages (above 10%) can reduce strength, while partial lime replacement (e.g., 50%) has improved physico-mechanical properties in stabilized earth blocks (SEBs) [8,25]. Full cement replacement with lime often reduces mechanical strength, though combining lime with bio-based additives, such as sugarcane ash, can yield positive outcomes [18]. Research in Mougheul has highlighted the potential of artisanal lime, produced traditionally with low energy input, to stabilize local clayey soils, offering a sustainable alternative to industrial lime [26,27]. These findings suggest that optimizing lime-cement ratios could balance performance and environmental benefits.

Growing interest in sustainable construction materials contrasts with limited research on artisanal lime, a locally produced, low-carbon stabilizer, for earth blocks in heritage preservation projects. While traditional stabilization methods often rely on industrial binders such as cement or industrial lime [18,19,28], the environmental and cultural benefits of traditionally produced lime, remain underexplored [29,30]. This study distinguishes itself through a rigorous evaluation of artisanal lime as a partial cement substitute in stabilized earth blocks, its targeted application to the restoration of heritage villages in arid climates, and a comprehensive analysis of physico-mechanical properties over extended curing periods, providing insights into long-term performance and contributing to sustainable, culturally appropriate construction practices.

Artisanal lime, also known as traditional lime, is produced through a time-honored calcination process using locally sourced limestone in traditional vertical kilns. Unlike industrial lime production, which relies on high-energy mechanized processes, artisanal lime production involves manual extraction of limestone rocks, crushing, and calcination in traditional kilns at lower temperatures over extended periods. This traditional method, still practiced in regions like Kenadsa, Algeria, results in a product with unique characteristics and significantly lower carbon footprint compared to industrial alternatives [31,32]. This study leverages the unique properties of artisanal lime to develop environmentally friendly stabilized earth blocks for construction and rehabilitation purposes.

2. Materials and methods

2.1. Materials

2.1.1 Soil

The soil used in this study was sourced from the old village of Mougheul (Fig. 1), a historic village in southwestern Algeria, renowned for its traditional raw earth architecture, often centuries-old, built with local materials and traditional techniques [23, 33]. These structures, now deteriorating due to environmental factors and lack of maintenance, require sustainable rehabilitation. This study develops stabilized earth blocks to restore Mougheul's heritage, ensuring compatibility with its cultural architecture.

The granular composition was carried out in accordance with the NF P 18-560 [34] standard in order to determine the size and proportion of different grains formed in the earth. The earth was composed largely of 63% of sand, 30% of gravel, and 7% of clay. It is also noticeable that the granular distribution curve of earth was recommended as band per CRATerre until 70% [28].

According to the division of the INRA reading triangle [35], the sample of earth was due to silty sand, which mentioned that its suitable for stabilization.

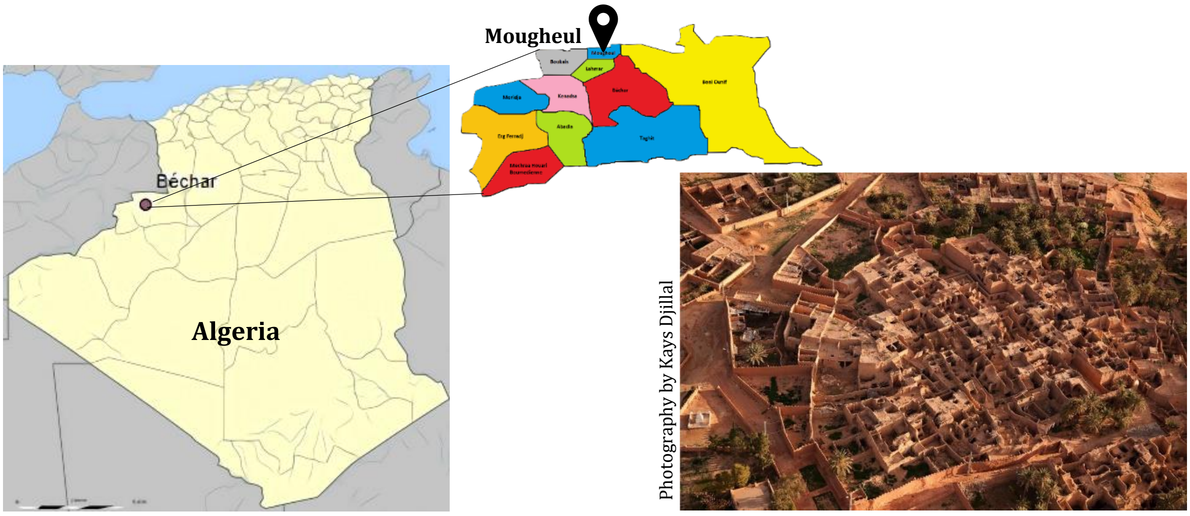

Fig. 1. Location map of Mougheul nd wide-angle aerial view of the old earthen brick village

The clay activity has been tested by the standards of limits Atterberg NF EN ISO 17892-12 [36] and methylene blue NFP 94-068 [37]. The modulus of plasticity Ip was 8.09 < 10 which confirmed the low plasticity of sample due to the decrease in quantity of clay. The less clay of sample leads to no shrinkage cracks, which is the cause of weakness of earth block.

The chemical composition of earth and artisanal lime, as presented in Table 1, was determined using X-ray fluorescence (XRF) spectroscopy at the chemical laboratory of the GICA Bachar cement plant, while data for cement and industrial lime were obtained from the manufacturers' technical datasheets. The XRF analysis enabled quantification of major and trace elements, revealing the mineralogical composition and potential reactivity of earth and artisanal lime. Samples were prepared following standard procedures, dried at 105°C for 24 hours, and ground to pass through a 75 µm sieve, ensuring a measurement accuracy of ±0.1% for major oxides. These data are critical for understanding the materials' properties and suitability for earth block stabilization.

Are shown in table 1, the elements of calcium oxide CaO, silicon oxide SiO_2, and aluminum oxide Al_2O_3 are the most oxidizing elements, which means that the earth was composed of a majority of minerals aluminosilicates and quartz. The high percentage of CaO compound explained the presence of large quantities of calcium and the red color of earth was due to the presence of large quantities of iron oxide F_2O_3.

2.1.2 Cement

The purpose of using white cement is to stabilize earth with the trade name "Malaki", it is a Portland composite cement (CPJ - CEM II / A-L 52.5N) with high primary and final strength manufactured by Lafarge plant and complied with Algerian standard NA442 [38] and European standard EN CE 197-1 [39]. The cement was composed of several oxidizing minerals; the most important was CaO as basic function, and SiO_2 as an acid. The type of white cement was used to maintain the natural color (red) of earth houses in this region, and thus an aesthetic architectural coherence. The physical and chemical properties are presented in Tables 1 and 2.

2.1.3 Industrial Lime

The industrial lime used in this study was quicklime (CaO) produced by BMSD plant. The physical and chemical properties are presented in Tables 1 and 2.

2.1.4 Artisanal Lime

The artisanal lime used in this research was quicklime (CaCOH) made in a traditional way in the city of Kenadsa, where the limestone rocks are extracted by geological sites located in this region [26]. Therefore, limestone was crushed to facilitate its combustion and placed on top of other combustible stones at the top of traditional vertical kiln, the fire was put in the lower part of kiln to start the calcination process of limestone [27]. The artisanal lime was extracted after two days of total cooling of kiln (Fig. 2). The extracted lime was crushed and sieved in an 80 µm sieve. The physical and chemical properties are presented in Tables 1 and 2.

Fig. 2. The stages in the manufacture of artisanal lime

Table 1. The chemical composition of materials (in %)

	CaO	SiO_2	Al_2O_3	F_2O_3	MgO	Na_2O	K_2O	TiO_2	P_2O_5	SO_3	$CaCO_3$	CO_2	Loss on Ignition
Earth	28.13	30.42	2.58	1.27	0.76	0.11	0.47	0.15	0.08	17.52			17.33
Cement	68	23.8	2.3	0.27	0.48	0.04	0.12			0.65			0.9
Industrial lime	>83.3	<2.5	<1.5	<2	<0.5	0.45	0.51			<0.5	<10	<5	
Artisanal lime	77.26	Insoluble rests = 13.58%									5.60		

Table 2. Physical properties of materials used in this study

Parameters	Earth	Cement	Industrial lime	Artisanal lime
Absolute density (g/cm³)	2.7	3.1	2.24	2.56
Apparent density (g/cm³)	1.3	1.14	0.72	0.87
Normal consistency		28±3.0	69.5	
Finesse following Blaine's method (cm²/g)		4300-5200	11663	10189
Shrinkage at 28 days (µm/m)		< 1000		
Expansion (mm)		≤ 3.0		
Initial setting time (min)		160 ± 40	80	
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			

2.2. Testing Method and Mix Proportions

Stabilized Earth Blocks (SEBs) refer to earth blocks enhanced with chemical stabilizers, such as cement or lime, to improve mechanical properties and durability. Unlike traditional mud bricks, SEBs incorporate binding agents without requiring compaction, offering a modern alternative for construction. In this study, SEBs are designed to replicate and enhance the traditional earthen bricks used in Mougheul's heritage structures while meeting contemporary performance standards. The experimental methodology combines standard testing procedures with adaptations specific to artisanal lime evaluation, as detailed in the following sections.

Previous studies [13,14,23,33] investigated stabilized earth blocks (SEBs) made from the soil of the Mougheul Ksar, consistently identifying an optimal composition with 10% cement as the control mix at a 0% replacement rate. In this study, cement was replaced with artisanal and industrial lime at rates of 0%, 12.5%, 25%, 50%, and 100%. Comparisons were made with the control composition (0% replacement), as shown in Table 3. The granular distribution of earth and mineralogical nature were considered uniform (constant) through all formulations.

Table 3. Details of the proportions of the mixture

Replacement rate	Cement	Artisanal lime	Industrial lime
0% (control)	10	0	0
12.5%	8.75	1.25	0
25%	7.5	2.5	0
50%	5	5	0
100%	0	10	0
12.5%	8.75	0	1.25
25%	7.5	0	2.5
50%	5	0	5
100%	0	0	10

Experimental test specimens are manufactured according to the classical method (Mixing - compacting - demolding). In order to prepare the mixing phase, the earth is dried in the oven at a temperature of 65°C for a period of 24 hours. We begin by weighing the appropriate quantities of each material according to the formulation composition, the assembly (earth + stabilizer) was manually mixed and left for 5 min, then the assembly (earth + stabilizer + water) is mixed with a 5-litre mortar mixer for a period of 2 minutes. The fresh mixture is placed in the molds of each experiment, then vibrated by a vibrating table for 15 seconds and stored in the laboratory. After two days of curing, the specimens are removed from the molds and left in an ordinary chamber, under (T= 22 ± 2°C and RH = 33 ± 5%), for up to 28 and 90 days of curing, to be subjected to various physico-mechanical tests. Photographs of the freshly molded and hardened earth blocks are presented in Fig. 3 and Fig. 4

Fig. 3. Photograph of fresh molded earth block

Fig. 4. Photograph of hardened earth block

2.3. Tests Protocol

2.3.1 Slump Test

The abrasive cone slump test was carried out in accordance with standard NF EN 12350-2 [40] in order to determine the workability of the concrete, as well as to obtain information on the ease of (mixing - compacting - transport and implementation) of the SEB in its fresh state.

2.3.2 Air Content Test

The air content test was conducted in accordance with NF EN 1015-7 [41], as this experiment focuses on measuring the volume of air entrapped in the fresh SEB, where we used a 0.75-liter aerometer (Fig. 5a), especially since the initial porosity (air bubble) is formed during the SEB mixing process.

2.3.3 Apparent Density Test

The density specimens were measured before each experiment. The procedure was intended to detect if there is no good compaction or bad mixing during the manufacture of bricks. The density $\rho = M/V_t$; is a physical greatness determined by dividing the weight of the sample M by the total volume V_t . The total test specimens of dimensions $10 \times 10 \times 5\ \text{cm}^3$ placed in a climatic chamber with conditions of 23°C and 50% RH. A balance with an accuracy of 0.01 was also used to measure the weight of the specimen with a caliper to measure its volume.

2.3.4 Total Water Absorption Test

This experiment was done by immersing the stabilized earth bricks completely in water for 24 hours and measuring the weight of the wet bricks from the initial dry weight according to the following relationship:

$$TWA(\%) = ((M_w - M_d)/M_d) \times 100 \tag{1}$$

2.3.5 Initial Absorption

The experiment of capillary absorption was carried out according to the XP P13-901 standard [42], by following the evolution of the open porosity of SEB. The specimens used are bricks of dimension $10 \times 10 \times 5\ \text{cm}^3$. The specimens were dried at 105 °C until the weight of sample was stabilized less than 0.1%. The base of specimen ($10 \times 5\ \text{cm}^2$) was partially immersed to a depth of 10 mm in which the initial absorption coefficient C_b represented the quantity of absorption in 30 minutes. This period was considered as a reference for the volume of largest pores (macrospores) located on the surface of SEB [14]. The initial absorption coefficient C_b was calculated according to the following relationship:

$$C_b = \frac{(M_h - M_d)}{S\sqrt{t}} \tag{2}$$

Where; $M_h - M_d$: The quantity of water absorbed during the test in kg, S: The area of the test piece in which the test was carried out in m^2, t: Immersion period in minutes.

2.3.6 Open Porosity

The open porosity was calculated based on the fundamental law of porosity $n = V_V/V_t$, where the total void volume Vv represented the quantity of water absorbed during half an hour per unit area divided by the total volume V_t as shown by the following formula:

$$n(\%) = \left(\frac{V_V}{V_t}\right)100\% = \left(\frac{\Delta m/\rho}{S\,.Z}\right)100\% = \left(\frac{\Delta m/s}{\rho\,.Z}\right)100\% \tag{3}$$

With; $\Delta m/s$: The quantity of water absorbed in the unit of surface area ($\text{kg/m}^2.\text{min}^{1/2}$), ρ: The density of water ($10^3\ \text{Kg/m}^3$), Z: The height of capillary imbibition front in (m).

2.3.7 Water Permeability

The water permeability test on earth blocks stabilized was conducted following a rigorous experimental protocol, adapted to the local resources of the university's geotechnical laboratory, in compliance with the ISO 17892-11:2019 standard for soil permeability tests [43].

A 10 cm cubic sample was placed between two metal plates to ensure uniform water pressure distribution on its upper and lower surfaces, with rubber sheets used to isolate the sample and prevent water concentration. The hydraulic conductivity (K_w) was calculated using the formula:

$$K_w = \frac{Q \cdot L}{A \cdot \Delta P} \tag{4}$$

Where; Q: Flow rate (m^3/s), L: Length of sample (m), A: Cross-sectional area (m^2), ΔP : The applied pressure (Pa).

The relationship between hydraulic conductivity K_w (m/s) and permeability k(m^2) is expressed by Darcy's law as $K_w = k(\rho g/\mu)$, where ρ is the fluid density (kg/m^3), g is the gravitational acceleration (m/s^2), and μ is the dynamic viscosity ($Pa \cdot s$). The intrinsic permeability k (m^2) reflects the material's ability to transmit fluid, independent of fluid properties.

2.3.8 Compressive and Flexural Strength

The flexural experiments were carried out according to the 3-point method on $40 \times 40 \times 160\ mm^3$ prismatic specimens (Fig. 5b). A CONTROLS universal testing machine, equipped with a three-point bending device and an automatic compression system (capacity 15/500 kN), was used for these tests. These experiments were conducted in accordance with standard NF EN 196-1 [44]. The flexural test was performed using a machine with a speed of 1.14 mm/min and the flexural strength was calculated according to the following law:

$$F_s = \frac{3}{2} \frac{F \times L}{b^3} \tag{5}$$

Where; b: The side of square section of prism, F: The force was applied in the middle of the prism, L: The distance between supports.

The compression experiments were conducted on $4 \times 4\ cm^2$ specimens obtained from the flexural experiment, where the specimen was exposed to an increasing load until failure and the compressive strength was calculated according to the following law:

$$\sigma_c = \frac{F}{S} \tag{6}$$

(a) (b)

Fig. 5. Various experiments applied to SEB

3. Results and Discussion

3.1. Consistence of Fresh SEB (Water Requirement)

The results, shown in Figure 6, indicated that higher cement replacement rates led to a firmer mixture, reflecting reduced workability. The decrease in workability can be explained by the decrease in quantity of water in mixture. Therefore, the decrease in quantity of water was due to the absorption of water during the dissociation of calcium oxide CaO resulted of calcium hydroxide

$Ca(OH)_2$. Water was used to separate $Ca(OH)_2$ in order to be transformed into Ca^{+2} ions while the cation exchange reaction occurred.

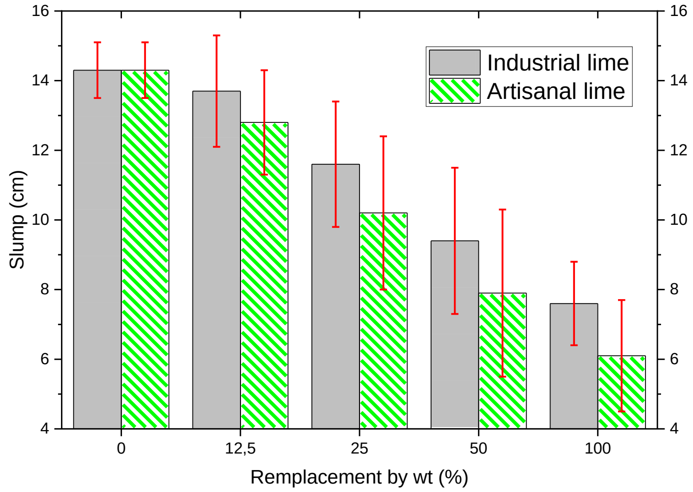

Fig. 6. Slump at Abrams cone

The use of artisanal lime resulted in lower degree of slump due to its greater absorption of water compared to industrial lime. This was due to the artisanal lime that contained more calcium oxide CaO compared to industrial lime (Table 1) with absorbing of water. Also, the increasing absorption of water can be explained by the cement replacement rate increased due to the large and increasing quantity of fines in the mixture, while the lime contained more fines than cement.

The obtained results corroborate the findings of Zebair et al. [23], who demonstrated that mixtures based on artisanal lime absorb more water, thereby reducing slump. Alexandre et al. [8] also confirm this trend, highlighting the effect of fine particles on workability. These observations indicate that lime-treated soils require higher water contents to maintain a consistency comparable to that of cement-treated soils. Regarding the class of our SEB, the results belong to the sections S2 and S3, and therefore to SEB; Plastic and medium workability, very plastic concrete with high workability, respectively. Qualitatively, this indicates a stiffer mix, potentially requiring more effort during compaction but leading to a more stable fresh product.

3.2. Air content

The results of the occluded air content, shown in Figure 7, indicate no significant effect of cement replacement by lime on occluded air. The replacement of cement by artificial lime with rates of 12.5% and 25% has no significant change in the indoor air content, while the rates of 50 % and 100% had a very small increase in the quantity of internal air with a percentage of 2.56 % and 5.13%, respectively, compared to the control composition.

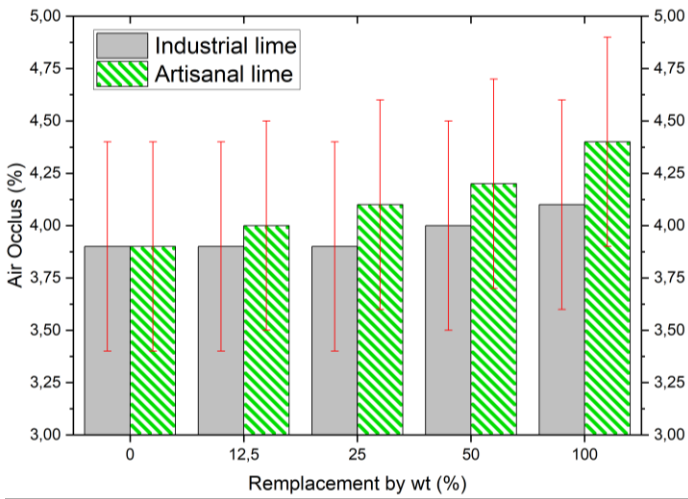

Fig. 7. Air content of SEB

In the case of artisanal lime, there was a direct proportional relationship between the high cement replacement rate and the increase in SEB's indoor air rate. The increase in rate of cement replacement by lime was accompanied by a slight increase in the content of entrapped air, which can be explained by the change in the internal mineralogical structure of the mixture. These findings are in agreement with Izemmouren et al. [21], who reported increased internal porosity and entrapped air with higher lime content. Alavéz et al. [18] corroborate these trends, attributing the slight increase in air content to microstructural changes caused by lime-induced chemical reactions. Qualitatively, this suggests that the stabilization process primarily affects the solid matrix rather than the air void structure at lower replacement rates.

3.3. Apparent Density

The density of SEB is illustrated in Figure 8. At first glance, a decrease in SEB density can be observed with increasing cement replacement rates. At 50% replacement, SEB density with artisanal lime reaches 1.92 g/cm^3, compared to 1.85 g/cm^3 for industrial lime, reflecting superior compactness suited to Mougheul's soils. This decrease is directly proportional to the replacement rate. Notably, the reduction in density was less pronounced with artisanal lime than with industrial lime, indicating that SEBs incorporating artisanal lime consistently exhibited higher densities than those containing industrial lime.

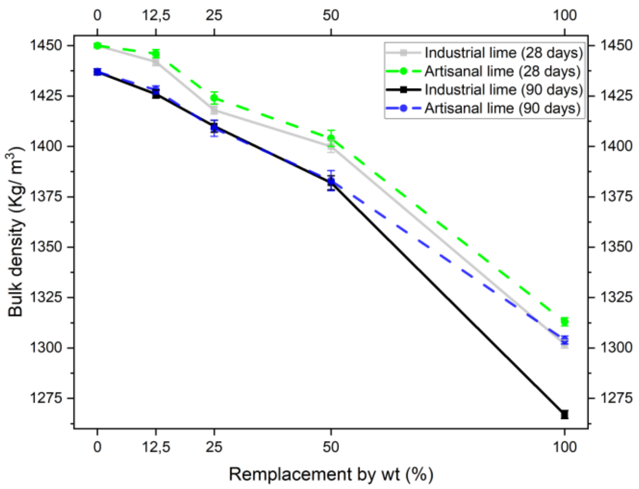

Fig. 8. The bulk density of SEB

This can be explained by the lower density of lime compared to cement and soil, which causes a reduction in the overall density of the mixture. Additionally, the agglomeration of soil particles following the addition of stabilizers (cement or lime) contributes to volume changes. This effect is particularly significant in lime-stabilized samples compared to those stabilized with cement [45]. Overall, the reduction in density observed with artisanal lime was smaller than that recorded with industrial lime.

3.4. Total Water Absorption

Figure 9 presents the variation in total water absorption at 28 and 90 days as a function of cement replacement rate. At 28 days of curing, an increase in the replacement of cement by lime resulted in a progressive rise in total water absorption. According to Alexandre et al. [8], total absorption increased by 17% when 50% of the cement was replaced with lime. Similarly, Guettala et al. [4] reported a 10.2% increase in total absorption at a replacement level of 37.5%.

At 90 days of curing, the results showed a slight improvement in total water absorption compared to the 28-day results. A reduction of approximately 2.25% and 0.78% in total absorption was recorded when 12.5% and 25% of the cement were replaced with industrial lime, respectively, compared to the control mix. Similarly, a 1.96% decrease in total absorption was observed when 12.5% of the cement was replaced with artisanal lime. This reduction is attributed to the formation of new hydration products, which filled the remaining voids after 90 days of curing. According to

Nagaraj et al. [25], the lowest total absorption value of 7.6% was obtained at a 50% replacement rate, followed by 8.3% at 0% replacement.

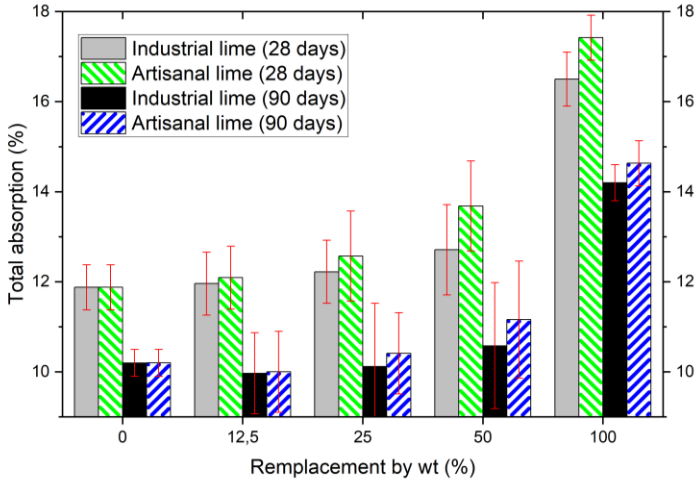

Fig. 9. Total absorption of SEB

Overall, the use of industrial lime consistently led to lower total absorption values than artisanal lime at all replacement levels. This is likely due to the higher production of calcium hydroxide $Ca(OH)_2$ from industrial lime, which promotes pozzolanic reactions with silica and alumina, generating additional hydration compounds that reduce porosity and water absorption. It can thus be suggested that mixtures with replacement rates less than or equal to 50% result in total absorption values lower than the 15% limit recommended by Indian Standards [46].

3.5. Initial Absorption

The results of the absorption coefficient in terms of replacement rate for different cure times were shown in Figure 10. The capillary water absorption was very rapid during the first 30 minutes of the experiment. This phase corresponds to the initial absorption, which is primarily the filling of large pores (macropores). The second phase occurred after the first 30 minutes, where the absorption rate decreased progressively and eventually stabilized. This later phase involves the gradual filling of smaller pores (mesopores and micropores) [14]. In the present study, only the first stage was considered.

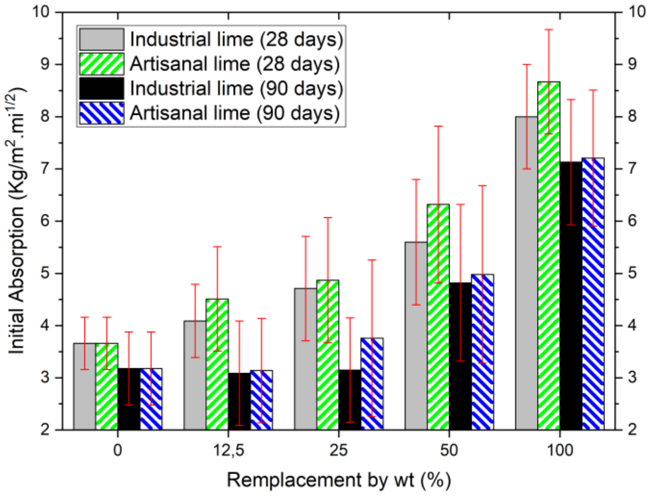

Fig. 10. Initial absorption of SEB

At 28 days of curing, all replacement rates resulted in higher initial absorption values compared to the control mixture. At 90 days, initial absorption of SEB with 12.5% artisanal lime is 0.45 g/cm^2, compared to 0.42 g/cm^2 for industrial lime, suited to Mougheul's arid conditions. The smallest recorded increase was 11.75%, corresponding to a 12.5% replacement of cement with industrial lime. The water absorption of stabilized earth blocks (SEB) depends on pore topology and hydration kinetics, as the increasing lime content alters the microstructure. Guettala et al. [4] also observed a 4.5% increase in capillary absorption when 37.5% of cement was replaced with lime.

At 90 days, the initial absorption values decreased compared to the 28-day results. This reduction can be explained by the hypothesis that hydration and pozzolanic reactions continue to progress over time, leading to refinement and partial closure of capillary pores. At a 12.5% replacement rate, a beneficial effect of the cement–lime combination was observed. Compared to the control, the initial absorption decreased by 2.83% and 1.26% for industrial and artisanal lime, respectively. It can be concluded that replacing cement with 12.5% lime leads to a significant reduction in initial water absorption over long-term curing. This improvement may be attributed to the change in pore geometry and distribution induced by lime addition.

3.6. Open Porosity

The results of the open porosity of SEB are shown in Figure 11. Porosity is one of the most critical structural properties, significantly influencing the transport and mechanical behavior of materials [47]. In earth stabilization, reducing the void spaces between particles is a primary objective, making porosity a key performance indicator. At 28 days of curing, the results showed a general increase in porosity with increasing replacement rates. This increase was proportional across all substitution levels. At 90 days, SEB porosity with 12.5% artisanal lime is 24.5%, compared to 23.8% for industrial lime. The rise in pore volume explains the observed decrease in density, which results from reduced compactness of the matrix.

On a microstructural level, the increase in porosity is attributed to the decline in calcium silicate hydrate (C-S-H) formation and the simultaneous increase in portlandite $Ca(OH)_2$. Replacing cement with lime leads to a reduction in hydration reactions and a rise in carbonation processes. The latter is considered detrimental to earth stabilization [45]. Additionally, the exposure of portlandite to air promotes the formation of calcium carbonate $CaCO_3$, which forms weak and brittle cementitious bonds, resulting in poor pore closure [48].

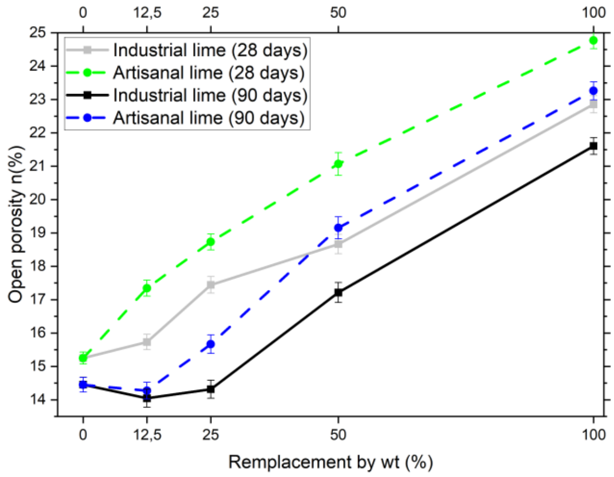

Fig. 11. Porosity of SEB on 28 and 90 days

After 90 days of curing, all formulations exhibited reduced porosity compared to their 28-day values at the same replacement rates. This reduction is due to the sustained presence of moisture, which facilitates the continuation of hydration and pozzolanic reactions. Notably, at a 12.5% replacement rate, porosity decreased relative to the control composition, suggesting a denser microstructure with reduced void content. This observation confirms the earlier hypothesis proposed in the (initial/total) absorption analysis regarding improved pore structure at this specific replacement rate. Finally, it is worth noting that the highest increase in porosity remained below 30%, which is still considered low porosity according to Dhir and Jackson [49].

3.7. Water Permeability

Permeability is one of the key parameters used to assess the durability of construction materials. Figure 12 shows the evolution of water permeability with respect to different cement replacement rates. At 28 days of curing, no data on hydraulic conductivity were available due to the incomplete execution of tests for most formulations. Nevertheless, the specimens exhibited high water permeability. This behavior can be attributed to the large pore sizes, high pore interconnectivity, and lower resistance to water flow typical of this early curing stage.

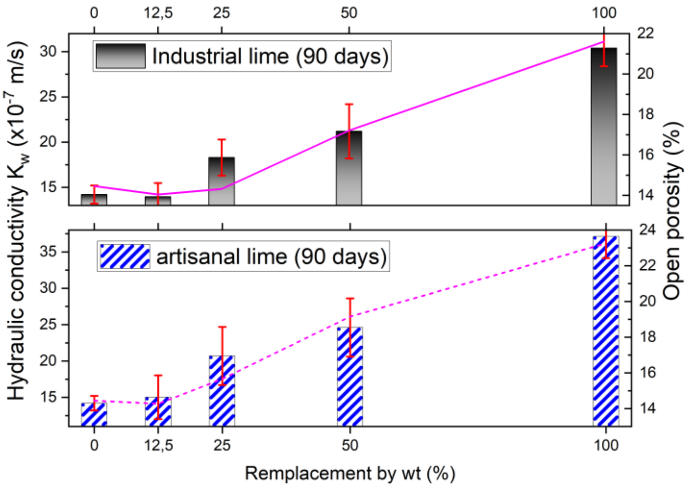

Fig. 12. Water permeability of SEB

At 90 days of curing, a general increase in hydraulic conductivity was observed with increasing replacement of cement by artisanal lime, indicating a proportional relationship. Notably, hydraulic conductivity increased by approximately 2.6 times between the 0% and 100% replacement rates. This observation aligns with the findings of Alexandre et al. [8], who reported a threefold increase in conductivity when 50% of the cement was replaced by lime. This comparison highlights the varying effects of different lime types and dosages on hydraulic conductivity, emphasizing the importance of optimizing mix proportions for desired performance. Interestingly, a 12.5% replacement rate led to a 1.62% decrease in hydraulic conductivity compared to the control composition. This reduction is consistent with a decrease in porosity and pore connectivity, as confirmed in the previous capillary absorption and open porosity experiments.

Beyond the 12.5% replacement rate, hydraulic conductivity continued to increase with higher substitution levels, indicating a progressive deterioration of the pore structure.

3.8. Compressive and Flexural Strength

Compressive strength and flexural results in term of replacement rates are shown in Figures 13 and 14, respectively. At 28 days of curing, increasing the replacement rates of cement with artisanal lime resulted in a decrease in compressive strength. The control sample (0% replacement) exhibited the highest compressive strength value of 1.94 MPa, due to the high degree of cement hydration. According to the plant's technical documentation, the cement used contained over 55% alite (C_3S), which reacts as follows:

$$C_3S + 3H \rightarrow C-S-H + 2CH \tag{7}$$

This reaction is known for its rapid rate and high early strength contribution at 28 days [49]. Moreover, the cement showed good compatibility with the gravel and sand matrix, as these coarser particles were effectively coated by the finer cement particles [50].

In the previous section, it was established that the soil used belongs to the silty sand class. Therefore, the compressive strength observed at 28 days was only moderate to low for mixes with lime, due to the limited formation of hydrates (CSH/CAH). This is attributed to the slow nature of the pozzolanic reaction at ambient temperature [45]. Additionally, Meukam et al. [51] confirmed that compressive strength development remains very low after the 28-day mark when lime is used. Recent studies on sustainable earthen materials, such as Cappai and Pia [52], suggest that thermal treatments can enhance surface resistance and long-term durability of lime-stabilized earth blocks, potentially mitigating the slow pozzolanic reaction rates observed in ambient conditions.

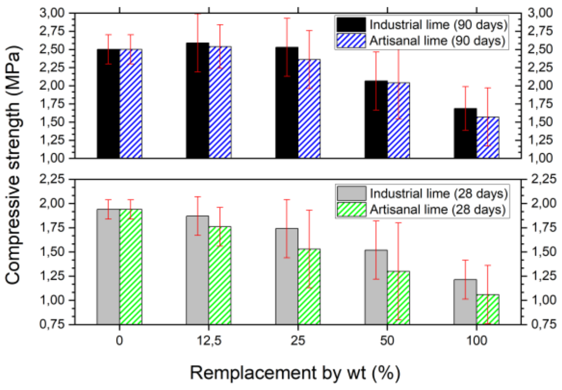

Fig. 13. The compressive strength of SEB

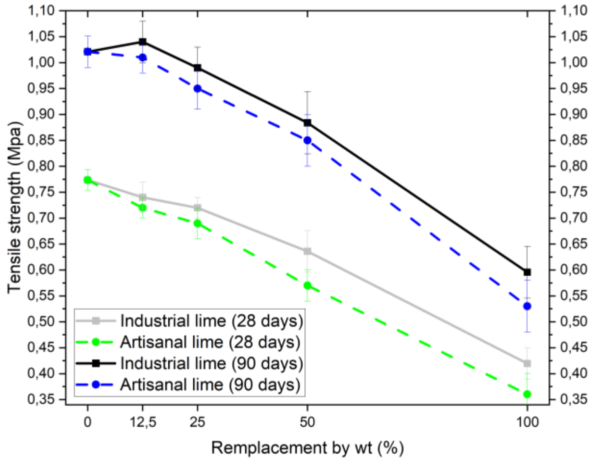

Fig. 14. Flexural strength of SEB

At 90 days, compressive strength increased notably at 12.5% and 25% replacement rates compared to the control composition. However, a decline was observed at higher substitution levels of 50% and 100%. The initial increase in strength at lower substitution levels is explained by the presence of sufficient lime (12.5–25%) interacting with the soil's 7% clay fraction. This interaction enhanced ionization, raising the pH and releasing Ca^{2+} and OH^{-} ions. In turn, the clay fraction released Al_2O_3 and SiO_2, which reacted with calcium and hydroxyl ions in the presence of water to form additional hydrated compounds (C-A-H and C-S-H) through pozzolanic reactions. This was in addition to the C-S-H already formed by cement hydration, leading to a denser matrix with smaller pores and fewer microcracks—ultimately improving compressive strength.

Conversely, at 50% and 100% replacement rates, compressive strength declined. This was due to a significant reduction in C_3S content, which limited cement hydration. Moreover, the clay fraction in the soil became exhausted, halting the release of alumina and silica. Consequently, pozzolanic activity ceased, and carbonation reactions became predominant, forming calcite $CaCO_3$ instead of strength-contributing hydrates. These findings are consistent with previous studies:

- Alexandre et al. [8] reported a 43% reduction in compressive strength with 50% cement replacement
- Guettala et al. [4] observed a 4.89% decrease with a 37.5% replacement rate.
- Alavéz et al. [18] noted a 29% drop when replacing all cement with lime.
- Hossain et al. [22] found a compressive strength loss of 16% at 28 days and 20% at 90 days for 50% substitution.
- Nagaraj et al. [25] indicated that although the 0% replacement rate provided better strength in the first 4 months, the 50% replacement mix showed superior performance over 6 months to 5 years.

It is worth noting that all formulations, except the one with 100% lime replacement, fall within Houben's recommended compressive strength range (1.2–2.8 MPa) for stabilized earth materials. With regard to flexural strength, the results are presented in Figure 14.

On the basis of the results obtained, the increase in the rate of replacement of cement by lime caused a decrease in the flexural strength of all compositions. The 12.5% replacement rate by industrial lime was the exception, where the flexural strength increases by 1.87% compared to the control sample on the 90th days of curing. This increase at this composition was explained by the good development of hydration/pozzolanic reactions, and thus the increase of additional bonds in the matrix [48] . Alavéz et al. [18], noted a 29% decrease in flexural during the total replacement of cement by lime. Hossain found that flexure decreased by 18% [22], 26% during replacement by 50% on the 28 and 90th days of curing, respectively.

4. Conclusion

This observe aimed to evaluate the potential of artisanal lime as an eco-friendly stabilizer for Stabilized Earth Blocks (SEB) within the sustainable rehabilitation of earthen historical past, with a focal point on the village of Mougheul in southwestern Algeria. The findings confirm that partial alternative of cement with artisanal lime complements the physico-mechanical houses of SEBs at the same time as aligning with circular economy ideas and lowering environmental impact. Specifically, a 12.5% substitute fee became recognized as most suitable, reaching a compressive strength of 1.94 MPa at twenty-eight days, with advanced lengthy-term sturdiness and reduced water absorption (1.96%) and porosity (2.83%) at ninety days. Compared to business lime, artisanal lime exhibited slightly decrease stabilization efficiency however offered substantial environmental advantages because of its low-power, waste-minimizing production process. By valorizing neighborhood substances—native soil and traditionally produced lime—this technique not best preserves cultural background however also mitigates the CO_2 emissions associated with cement production, which debts for 8 % of global emissions. The adoption of artisanal lime as a stabilizer promotes low-carbon, fee-powerful creation practices, assisting Sustainable Development Goals (SDGs) and climate movement. These consequences study international requirements for earthen introduction and demonstrate compatibility with traditional earthen architectures.

The proposed SEBs offer a practical and sustainable solution for the rehabilitation and preservation of earthen structures in heritage contexts like Mougheul. Their application can range from repairing deteriorated walls and reconstructing collapsed sections to constructing new compatible infills within existing structures. By utilizing locally sourced earth and artisanal lime, these SEBs ensure material compatibility with the original construction, minimizing aesthetic and structural discrepancies. Furthermore, the enhanced durability and mechanical properties of the SEBs contribute to the long-term stability of rehabilitated structures, reducing the need for frequent interventions. This approach supports the conservation of cultural heritage by providing a robust, environmentally friendly, and economically viable alternative to conventional repair methods, which often rely on incompatible materials like concrete.

However, overall cement substitute with artisanal lime brought about a extraordinary decline in physico-mechanical performance, underscoring the importance of partial substitution. The examine's results have been prompted by using the particular dry and high-temperature climatic conditions of southwestern Algeria, which may additionally restrict their generalizability. To construct on those findings, future studies need to look into the long-term overall performance of SEBs under diverse climatic situations and explore synergies with different bio-based totally stabilizers. Such studies may want to similarly validate the scalability of artisanal lime in sustainable creation and enhance its software in ecological engineering for earthen history maintenance.

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