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Experimental Characterization of the Thermal and Mechanical Properties of Earth Bricks Stabilized by Alkaline Solution and Reinforced with Natural Fibers: A Comparative Study

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Abstract. The use of earth bricks is a sustainable and environmentally friendly alternative to traditional building materials. However, these bricks can be vulnerable to erosion and extreme climatic conditions, which may limit their use in arid and semi-arid regions. In this experimental study, the aim was to improve the thermal and mechanical properties of earth bricks by stabilizing them with a mixture of alkaline solution and reinforcing them with natural fibers (maize, reeds, and olive). To this end, we designed earth bricks with different fiber percentages (from 0% to 8% of soil weight) and a fixed percentage of alkaline solution of 1.5%. After 28 days, the bricks were subjected to an experimental study to assess their thermal and mechanical cleanliness. The results showed that bricks stabilized with a fiber percentage of 2% and 3% had the best mechanical properties. They also showed an increase in thermal resistance as the percentage of fibers used increased. In addition, these bricks had higher compressive and tensile strengths than unstabilized bricks. This experimental study demonstrated that stabilizing earth bricks with a mixture of alkaline solution and fibers significantly improved their thermal properties.

1. Introduction

in the field of construction and energy efficiency, it's essential to find sustainable, environmentally friendly building materials. Vernacular building materials such as earth have many environmental advantages: local availability, low embodied energy, low CO2 emissions, and biodegradability. They also offer social and economic benefits. However, The building industry is responsible for a third of all emissions, uses 40% of materials, and generates 40% of waste[1]. Using earth bricks in construction can cut carbon dioxide emissions by 80% compared to using fired bricks[2]. Furthermore, earth bricks have a lower structural strength than modern building materials such as reinforced concrete. They can be more prone to cracking and spalling, particularly under extreme climatic conditions such as earthquakes or heavy rain. Earth bricks are also sensitive to moisture. If not properly protected against water, they can deteriorate rapidly.

Stabilizing earth bricks can improve their structural strength and durability. This can be achieved by adding materials such as straw, renewable palm fibers, plant fibers, cement, lime or other admixtures to the raw earth during brick manufacture to strengthen the bricks and make them more resistant to weathering and mechanical stress. A study by A. Thennarasan Latha et al. examined the impact of adding soda-treated sisal fibers and cement to stabilized compressed earth blocks (CSEB). The findings revealed that the compressive strength of CSEB increases with the addition of cement up to 10%, but decreases beyond that. Additionally, the incorporation of 1%

30 mm sisal fibers with 10% cement resulted in the highest compressive strength, and the flexural strength of CSEB also improved with the inclusion of sisal fibers [3]. Another study by K. Bougtaib et al. investigated the effects of adding doum palm fibers and lime to hand-made compressed earth bricks (CEB). The results indicated that 10% lime and 1% fiber were the optimal proportions for maximizing the performance of earth bricks [5]. Furthermore, A. Jesudass, V. Gayathri, and R. Geethan et al. explored the use of natural fibers in earth blocks as a sustainable solution for enhancing thermal performance and durability [4]. E.B. Ojo et al. assessed the reinforcing effects of various fibers (sisal, eucalyptus pulp, polypropylene) and alkaline activators (NaOH and Na silicate) on the thermal and physical properties of earth bricks. The study revealed that a 2% sisal content provided the best strength-density balance, and polypropylene conferred strain-hardening behavior [6]. K. AlShuhail, A. Aldawoud, and J. Syarif et al. investigated how the addition of natural additives such as date palm fibers enhances the mechanical and physical performance of compressed earth bricks, making them more resistant to moisture [7]..(R. Mateus et al.) carried out an Environmental Life Cycle Assessment of earth building materials.This analysis found that vernacular earth building materials have a low environmental impact thanks to their local availability and low-energy manufacturing processes. They can help reduce the impact of buildings [8]. C.R. Ganesh, J. Sumalatha, K.S. Sreekeshava et al., the impact of adding ground granulated blast furnace slag (GGBS) and polypropylene geofibers on the properties of compressed stabilized earth blocks (CSEB) was investigated. The results showed that increasing GGBS enhanced the dry and wet compressive strength of CSEBs, while slightly reducing water absorption and block density. The optimal combination was found to be 30% GGBS, 5% lime, and 0.2% geofibers [9]. I. Bouchefra et al. examined the effects of treated and untreated doum fibers as an eco-friendly material. The study revealed that as the fiber content increased, the density of the fiber-reinforced composite decreased, with a reduction of up to 15.2% observed with 2% raw fiber. The compressive strength also decreased with higher fiber content, showing a decrease of 25% with treated fibers and 35% with 2% raw fibers. Additionally, the addition of fibers led to a slight decrease in thermal conductivity, with a reduction of 27% observed with 2% treated fiber. Increasing the compaction pressure from 4.75 to 9.7 MPa resulted in a 50% increase in compressive strength and an 11% increase in thermal conductivity. Furthermore, increasing the fiber length from 0.4 to 2.5 cm led to a 20% reduction in compressive strength. It was also noted that a cement content of 10% resulted in increased compressive strength by 7.5%, while a lime content of 9% provided maximum strength [10]. M. Saidi et al., the influence of stabilization on the thermal conductivity and moisture absorption capacity of compressed earth bricks was examined. The results indicated that the thermal conductivity of the earth bricks increased with higher cement and lime content [11].

The primary objective of this comprehensive comparative study is to evaluate both the thermal and mechanical characteristics of earth bricks that have been stabilized with an alkaline solution and reinforced with a range of renewable natural fibers. These fibers include reed, corn, and olive, and the study aims to analyze how these additions impact the overall properties of the earth bricks, with a specific focus on their thermal conductivity, density, and mechanical strength.

2. Materials and methods

2.1 Materials

2.1.1 Soil

The soil used in our study comes from the Errachidia region in south-eastern Morocco. This soil is a very fine material and is widely used in construction work due to its ideal properties for certain types of structures (fig.1) . Errachidia clay is renowned for its ability to absorb water, making it highly resistant to temperature fluctuations. This property is particularly useful in regions where temperatures can vary considerably over the course of a day or season.

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Fig.1 : The soil of Errachidia

2.1.2 Alkaline Solution

For the synthesis of geopolymers between soil and alkaline solution, we used commercial alkaline solutions of sodium aluminosilicate (AlNa12SiO5) and sodium hydroxide (NaOH) (fig.2) . These alkaline solutions, also known as activator solutions, are used to form geopolymers, which are inorganic polymers formed by a chemical reaction between a siliceous material and an alkaline activator. Geopolymers have a dense crystalline structure and are known for their resistance to deformation and degradation, making them highly durable building materials.

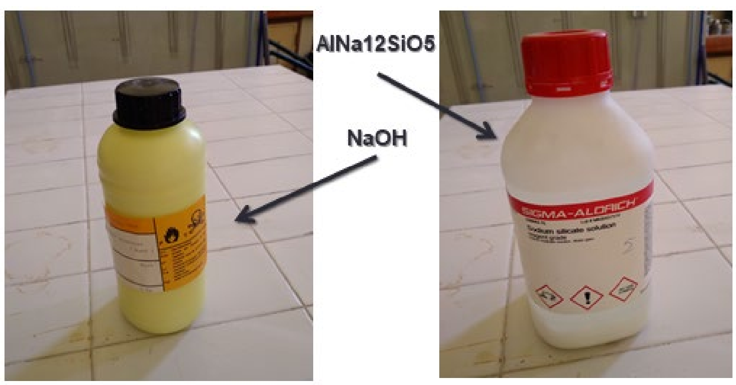

Fig.2. Alkaline solutions of sodium aluminosilicate (AlNa12SiO5) and sodium hydroxide (NaOH).

In this study, we utilized renewable natural fibers such as reeds, corn fibers, and olive fibers. The reeds were harvested from the oases of Errachidia, near the river. The corn and olive fibers were obtained from corn and olive waste, which were collected and cleaned before being dried for use (fig.3).

Fig.3 Fibers of (a): reeds, (b): corn, (c): olive.

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2.2 The experimental procedure

Sample preparation involved mixing soil and fibers in varying percentages ranging from 0% to 8%. Next, we added the alkaline solution and water, with a fixed optimum percentage of alkaline solution of 1.5% by weight of water. Mixing was carried out manually, then the bricks were designed using specific molds. The dimensions of the molds are 24×24×4 cm^3 (for thermal testing), and cylindrical molds with diameter D= 10 cm and height H= 20 cm (for mechanical testing).
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Fig.4. Bricks prepared after demolition.

After demolding, the bricks were carefully removed from the molds and placed in our laboratory for a natural drying process. This step was essential to allow the bricks to harden and stabilize before being subjected to further testing. During this 28-day drying period, the bricks were kept in a controlled environment. This was to avoid any distortion or deformation of the bricks during the drying process. Natural drying allowed the bricks to gradually lose their water content, helping to strengthen their structure and improve their mechanical strength. This drying stage is crucial to guaranteeing the quality and durability of the bricks, minimizing the risk of subsequent cracking or deformation. (fig.4) .

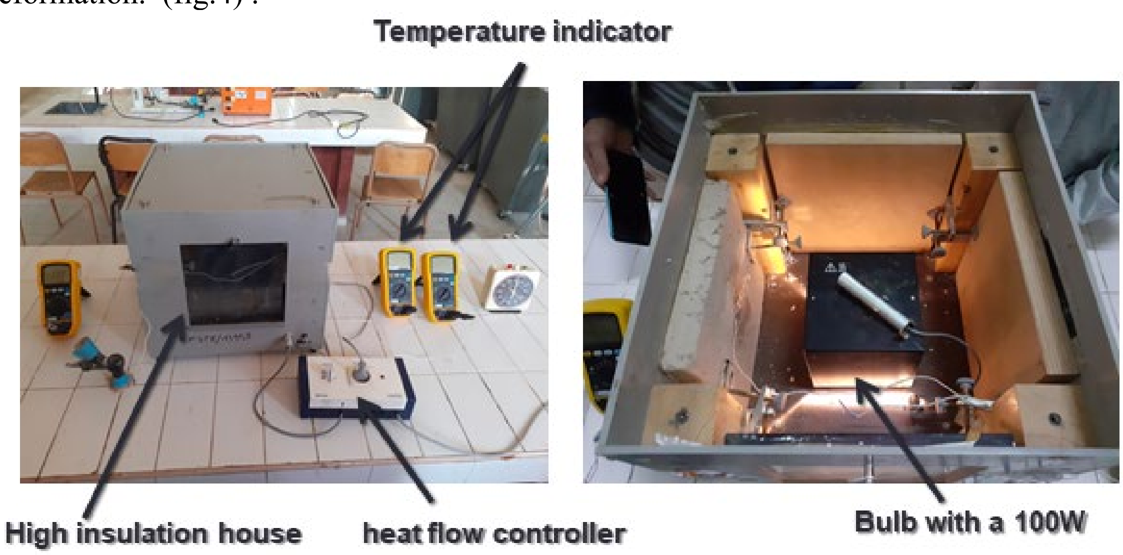

Fig.5 : Thermal house

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In this study, we utilized a thermal conductivity measurement device known as the thermal house (fig.5) with interchangeable walls measuring 40x40x40 cm^3. This apparatus has been extensively detailed in various publications for determining the thermal conductivity of building materials in controlled laboratory conditions, with an uncertainty of under 10% [13-12]. The thermal enclosure consists of four side walls, each featuring a square aperture measuring 21x21 cm^2, which can be sealed using a 5 cm thick polystyrene sheet known for its exceptional insulation properties. To produce heat and minimize the influence of radiation, a 100 W incandescent lamp enclosed in a small black box was utilized. Furthermore, a thermal regulator was employed to sustain an internal temperature of 50°C, while an air conditioner was used to maintain the room temperature at 20°C.

During the trial, the specimen to be analyzed, measuring 24x24x4 cm^3, was positioned on one of the side walls of the thermal enclosure, with the remaining walls sealed using polystyrene panels to prevent heat dissipation. Thermocouples with an uncertainty of +/-0.7°C were employed to monitor temperature changes inside and outside the thermal enclosure. These temperature fluctuations were recorded using a data acquisition system. Once a stable condition was reached (approximately 6 hours after the commencement of each measurement), the temperature data were utilized to estimate the thermal conductivity.

In computing the thermal conductivity, we took into account the conservation of heat flow arising from convection between the internal air and the inner wall surface, as well as convection between the external air and the outer wall surface. Additionally, conduction through the sample was taken into account:

$$\varphi = h_{int}(T_{loc} - T_{int})S = S \times \lambda \frac{T_{int}-T_{ext}}{e} = h_{ext}(T_{ext} - T_{amb})S \qquad \text{(Eq.1)}$$

With :

- h_{int}: internal convection coefficient.
- h_{ext}: external convection coefficient.
- T_{int}: temperature of the inside of walls.
- T_{ext}: temperature of the outside of the wall.
- T_{loc}: air temperature inside thermal house.
- T_{amb}: ambient temperature.
- e: wall thickness.

We calculated the thermal conductivity (λ) by applying Equation (Eq.1) with a heat transfer coefficient of 8.1 W/m²K [14,13]. The assessment of our samples' thermal conductivity adhered to the prescribed methodology outlined by the manufacturer (PHYWE). This procedure entailed the utilization of a PHYWE thermal control stand, along with a set of thermocouples for monitoring temperature fluctuations both inside and outside the thermal housing [15]. We recorded the readings once the thermocouples had stabilized, ensuring that the system was close to equilibrium (approximately 8 hours after the start of the measurement)

$$h_{int}(T_{loc} - T_{int}) = \frac{\lambda}{e}(T_{int} - T_{ext}) \qquad (Eq.2)$$

$$\lambda = \frac{(T_{loc}-T_{int})}{(T_{int}-T_{ext})} \times h_{int} \times e \qquad (Eq.3)$$

with:

- e = 0,04 m.

To assess the mechanical compressive and tensile strength of the samples, we used a FORM TEST SEIDNER hydraulic press (fig. 6). This device applies a controlled mechanical force to the samples to measure their strength.

The force applied to the samples during compression and tensile tests is measured using a load cell integrated into the hydraulic press. This load cell converts the applied force into a numerical value, which is then used to calculate the mechanical strength of the samples.
Mechanical strength is calculated using the following relationship:

$$\text{Mechanical strenght} = \frac{Applied\ force}{Sample\ surface} = \frac{F}{r^2 * \pi} \qquad \text{(Eq.4)}$$

Fig.6: SEIDNER FORM TEST 500KN hydraulic press

3. Results and discussion

3.1 The effect of natural fiber content and alkaline solution

3.1.1 Conductivity and thermal resistance

The findings of the study indicate that the thermal properties of earth bricks are affected by the presence of reed, corn, and olive fibers, as well as the type of alkaline solution used for stabilization. The study maintained the percentage of alkaline solution at 1.5% relative to the weight of water.

Figure 7 illustrates the changes in thermal conductivity and thermal resistance with varying fiber content. It was observed that the thermal conductivity of alkaline-stabilized earth bricks reinforced with natural fibers decreases as the fiber content increases. For corn fiber contents ranging from 0% to 8%, the thermal conductivity of the blocks was measured at 0.702, 0.7, 0.642, 0.6, 0.58, 0.42, 0.41, 0.38, and 0.32 W/mK. Similarly, the thermal conductivity of the blocks reinforced with reed and olive fibers reached values of 0.566 W/mK and 0.501 W/mK, respectively, for a fiber content of 8%. Additionally, it was noted that the thermal resistance of the earth bricks increased in proportion to the increase in fiber content. This is due to the fibers creating air spaces within the bricks, which act as thermal insulation. These air pockets impede the transfer of heat through the material, resulting in an increase in thermal resistance [16,17,18].

This study's results align with previous research demonstrating the impact of natural fibers on the thermal properties of construction materials [19,20]. The findings suggest that the incorporation of natural fibers in earth bricks can be a viable strategy for enhancing their thermal performance, potentially leading to more energy-efficient and sustainable construction practices.

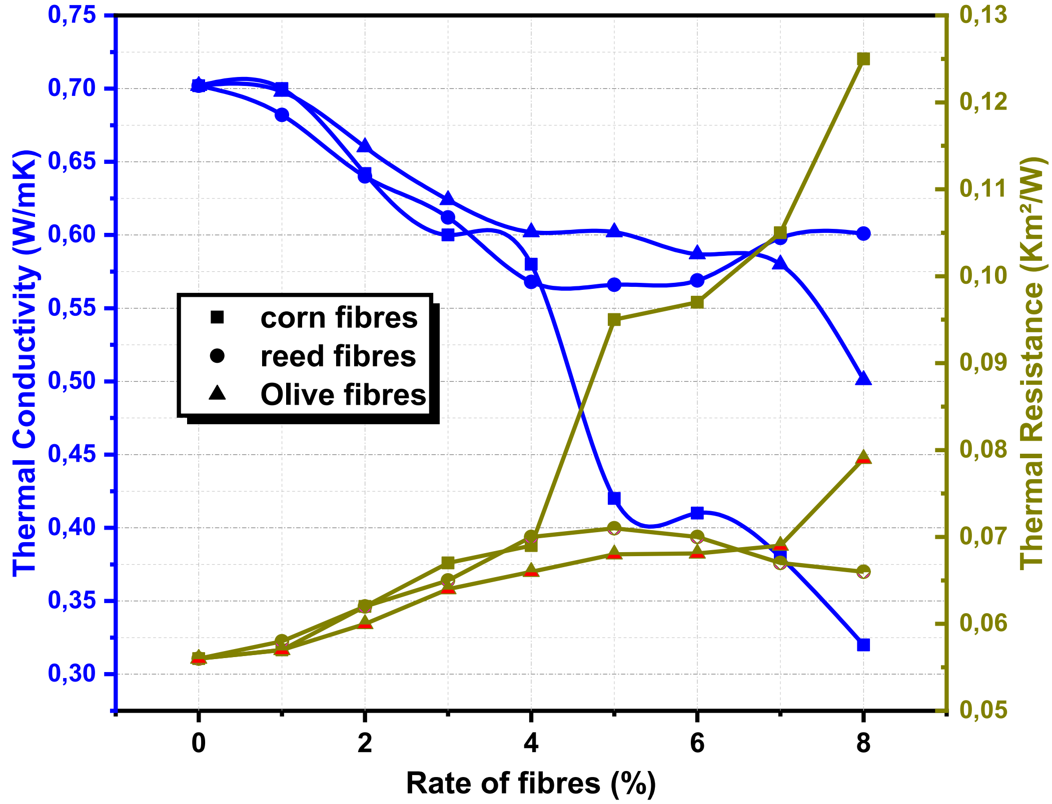

Fig.7. The variation of thermal conductivity and resistance of the clay bricks studied.

The incorporation of reed, corn, and olive fibers in alkaline-stabilized earth bricks leads to a reduction in thermal conductivity and an increase in thermal resistance. This highlights the potential of using natural fibers as reinforcement in earth construction to enhance thermal insulation properties and improve energy efficiency in buildings.

3.1.2 Compressive and tensile strength

In our mechanical testing, we examined both unstabilized and unreinforced bricks, and found that they exhibited compressive and tensile strengths of 4.2 MPa and 0.82 MPa, respectively (see fig.8). Upon the addition of corn fiber and alkaline solution, the compressive strength increased to a peak of 5.78 MPa with 2% corn fiber, after which it began to decrease. Meanwhile, the tensile strength rose to 1.6 MPa with 1% fiber content. When reed fiber was introduced, the compressive strength reached 6.1 MPa with 3% fiber, and the tensile strength increased to 1.8 MPa. Finally, olive fibers led to a maximum compressive strength of 6.4 MPa with 2% fiber content, and a maximum tensile strength of 1.8 MPa with 3% fiber content.

These results are consistent with previous studies that have demonstrated the potential of natural fibers to enhance the mechanical properties of construction materials [21,22,23]. The findings suggest that the incorporation of specific natural fibers, such as corn, reed, and olive fibers, in earth bricks can significantly improve their compressive and tensile strengths, which is crucial for the development of more durable and resilient construction materials.

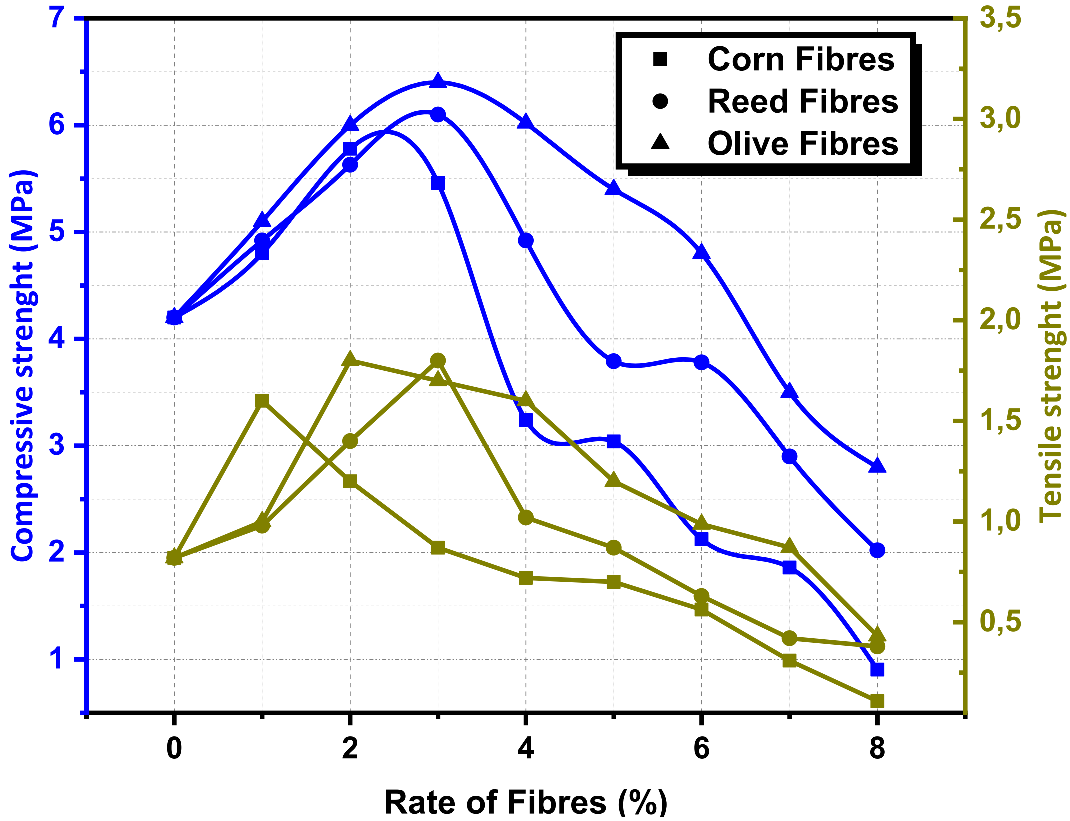

Fig.8: the variations of compressive and tensile strength of samples

Above a certain optimum percentage (between 2% and 3%, depending on the type of fiber), the addition of more fiber can lead to a reduction in the mechanical strength of the composite material. This can be due to several factors. Firstly, too many fibers can overload the material, compromising its cohesion and overall strength. In addition, too high a fiber content can lead to poor dispersion of the fibers in the matrix, reducing their effectiveness in terms of reinforcement.

However, it is important to note that mechanical performance also depends on the type of fibers used. In the case of olive fibers, they appear to offer the best mechanical performance for this composite material. Olive fibers have unique characteristics that make them particularly suitable for reinforcing the material matrix.

Conclusion

The objective of this experimental investigation was to evaluate the impact of incorporating renewable natural fibers such as reeds, corn, and olives, along with an alkaline solution comprising sodium aluminosilicate (AlNa12SiO5) and sodium hydroxide (NaOH), on the thermal and mechanical characteristics of earth bricks. The findings demonstrated that the utilization of these additives in stabilizing earth bricks significantly enhanced their performance. The introduction of fibers resulted in a decrease in thermal conductivity and an enhancement in the thermal resistance of the bricks, thereby imparting improved insulating properties. Moreover, the fibers contributed to an enhancement in the mechanical compressive and tensile strength of the bricks. Optimal outcomes were achieved with a fiber dosage of approximately 2-3% by mass and a consistent percentage of alkaline solution at 1.5%. Beyond this dosage, an excess of fibers tended to diminish the mechanical properties of the bricks. Among the various fibers examined, olive fibers exhibited the most favorable performance in this study.

These results underscore the substantial potential of stabilized earth bricks for environmentally friendly and sustainable construction, particularly in semi-arid regions where they can endure extreme climatic conditions. Their production from local materials renders them a promising substitute for traditional materials. Further research will be essential to refine the performance of these bricks and investigate their applicability in diverse construction scenarios.

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