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Effect of Olive Pomace Content on the Capillary Water Absorption Behaviour of Earth-Sand Bio-Based Composites for use on sustainable construction

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Abstract

Evaluating the hydraulic properties of construction materials is an essential step in determining their durability and in-service behavior. Among the commonly used methods, the capillary absorption test is a simple and effective tool for characterizing a porous material's ability to absorb and transport water under the influence of capillary forces. This property is of particular importance for bio-based materials and earth-matrix composites, whose performance is strongly influenced by their porous structure. This study focuses on the characterization of earth-sand composites incorporating olive pomace as a bio-based reinforcing material. The main objective is to evaluate the influence of different olive pomace contents on the capillary behavior of the developed composites. Capillary absorption tests were conducted on several formulations containing varying percentages of olive pomace. The results obtained are analyzed in terms of the bulk density, porosity, and microstructural organization of the material. The incorporation of olive pomace significantly alters the physical characteristics of the composite by increasing porosity and reducing the density of the soil matrix. These changes directly influence water transport mechanisms and capillary absorption kinetics. Analysis of the results reveals a gradual decrease in water absorption as the olive pomace content increases, reflecting greater connectivity within the pore network. The results obtained show that the capillary absorption test is a relevant method for evaluating the hydraulic behavior of olive pomace-reinforced soil-sand composites. This approach allows for an assessment of their suitability for use in sustainable construction applications while contributing to a better understanding of the relationships between formulation, porosity, and moisture transfer.

Keywords: *Raw earth, Bio-based composite, Capillary absorption, Porosity, Sustainable construction.*

I. Introduction

Earth-based building materials have attracted renewed interest in recent years as sustainable alternatives to conventional construction materials owing to their low environmental impact, local availability, low embodied energy, and excellent hygrothermal performance [1], [2]. Their use contributes to reducing greenhouse gas emissions while promoting the valorization of locally available resources within a circular economy framework. However, despite these advantages, earthen materials remain highly sensitive to moisture, which directly affects their physical, mechanical, thermal, and durability properties.

To improve the performance of earth-based materials while enhancing their sustainability, considerable research has focused on the incorporation of agricultural by-products as natural reinforcements. This approach not only promotes the valorization of agro-industrial waste but also improves several physical, mechanical, and thermal properties of earthen composites [3]. Among the various agricultural residues investigated, olive pomace has emerged as a particularly promising bio-based reinforcement because of its low density, abundant availability in olive-producing regions, renewable nature, and favorable thermal insulation properties [4], [5], [6]. Furthermore, its use represents an environmentally friendly solution for valorizing one of the major by-products generated by the olive oil industry.

The water behaviour of earthen materials is a key factor governing their suitability for construction applications. Moisture ingress directly influences dimensional stability, mechanical strength, thermal performance, and resistance to weathering. Among the various methods used to characterize water transport, the capillary water absorption test is widely recognized as one of the most appropriate techniques for evaluating the ability of porous materials to absorb and transport water through capillary action [7], [8], [9]. This phenomenon mainly depends on pore size distribution, pore connectivity, total porosity, and the intrinsic characteristics of the material constituents.

The incorporation of olive pomace into a clay–sand matrix modifies the composite microstructure by increasing its porosity and altering the organization of the pore network. These microstructural changes influence moisture transfer mechanisms and consequently affect the hydraulic behaviour and durability of the material. Therefore, investigating capillary water absorption provides valuable insight into the influence of plant-based reinforcement on water transport mechanisms and the overall performance of the developed composites [10], [11].

The present study forms part of our ongoing research on the development and characterization of bio-based earthen composites reinforced with olive pomace [12]. The present contribution focuses on the hydraulic behaviour of these materials through the analysis of capillary water absorption. The objective is to evaluate the influence of different olive pomace incorporation rates on the capillary absorption behaviour of clay–sand composites and to establish correlations between this property and the main physical characteristics of the materials, including bulk density, porosity, and water-accessible pore structure. This work therefore completes the characterization of the developed composites and contributes to a comprehensive understanding of their hydro-mechanical and thermo-physical behaviour for sustainable construction applications.

II. Material and methods

This research focuses on the development of an eco-material composed of three main components: raw earth, sand, and olive pomace. This mixture aims to create energy-efficient bricks by utilizing local resources and agricultural waste. [12]

II.1 Raw materials

Here is a detailed description of these base materials:

II.1.1 Raw Earth

- Origin and nature: It was sourced locally in the Akbil region (Tizi Ouzou, Algeria). It is a reddish-ochre clay-loam soil.
- Role: It serves as the main matrix and natural binder of the composite due to its ability to form a cohesive structure after drying.

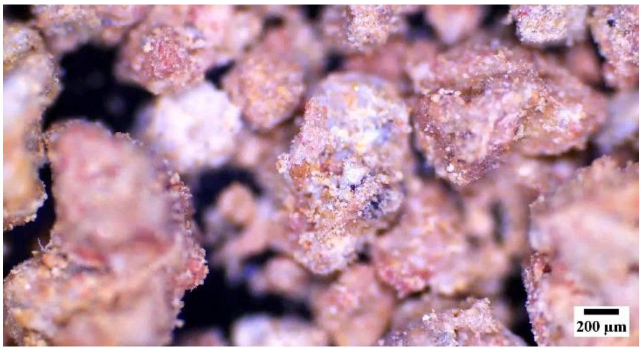

Figure 1. Raw earth Particles under Optical Microscope

II.1.2 Sand

- Origin: It comes from a local quarry and consists of light beige siliceous grains.
- Function: It is used as a granular stabilizing agent to reduce the plasticity of the soil mixture. Its function is to form a stable granular skeleton that improves mechanical strength and limits cracking and thermal shrinkage.

Figure 2. Sand Particles under Optical Microscope (200 µm)

II.1.3 Olive Pomace

- Origin: This is a solid byproduct of olive oil extraction, sourced from a local oil mill (Tizi Ouzou). It consists of crushed olive pits.
- Role: It serves as a lightweight, organic aggregate. Its incorporation aims to increase the material's porosity to improve thermal insulation (reducing thermal conductivity) and reduce the weight of the bricks.
- Preparation: Before use, it undergoes a cleaning process (washing with warm water) and is dried at 105°C to remove moisture.
- Properties: It is a porous, fibrous material with a low absolute density (1.15 g/cm³). It contains organic compounds such as lipids and esters.

Figure 3. Olive Pomace Particles under Optical Microscope (200 µm)

II.2 Raw materials characterization

Tests to Determine the Physical Properties of Base Materials

The physical characterization of the materials comprising the composites under study is a fundamental step in the development and performance evaluation of earth-matrix bricks reinforced with plant-based additives. These identification tests allow for the determination of the geotechnical and physical properties of raw earth, sand, and olive pomace in order to optimize the formulation of the mixtures and evaluate the influence of plant-based additives on the overall behavior of the composite. [12], [13].

In this study, several standardized tests were conducted in accordance with French AFNOR standards to ensure the reliability and reproducibility of the experimental results.

II.2.1 Characterization of Raw Earth and Sand

1- Particle Size Analysis

The particle size analysis was performed in accordance with standards NF P18-560 and NF P94-057 to determine the size distribution of the particles comprising the raw earth and sand. This characterization allows for the evaluation of the material's texture and the identification of the proportions of the various granular fractions (gravel, sand, silt, and clay).

The test involves passing the dry sample through a series of standard sieves of decreasing size to determine the percentages retained and passed by each sieve. The results obtained allow for the plotting of particle size distribution curves and the evaluation of the homogeneity of the materials studied.

For fine particles smaller than 80 µm, a sedimentation-based particle size analysis was also conducted in accordance with standard NF P94-057. This method is based on the settling velocity of particles in a fluid, in accordance with Stokes' law. It allows for the precise characterization of the silt and clay fractions present in the raw earth.

2- Sand Equivalent Test

The sand equivalent test was conducted in accordance with standard NF P18-598 to assess the cleanliness of the sand used and to quantify the presence of fine clay or silt particles that could influence the mechanical and hydraulic properties of the composite.

The principle of the test is based on the separation of sandy particles and fine particles in a flocculating solution. The ratio of the height of the settled sand to the total height of the suspension is used to calculate the sand equivalent value. A high value indicates clean sand with a low content of clay fines.

Figure 4. Sand Equivalent Test Apparatus.

3- Standard Proctor Test

The standard Proctor compaction test was conducted in accordance with standard NF P94-093 to determine the optimum moisture content and maximum dry density of the various mixtures under study.

Figure 5. Experimental Setup for the Standard Proctor Test.

The test involves compacting the material in a standard Mold in multiple layers using a specified compaction energy. For each moisture content, the corresponding dry density is calculated to plot the Proctor curve. The peak of this curve identifies:

- the optimum moisture content;

- the maximum dry density.

These parameters are essential for determining the optimal conditions for the application of the composites under study.

4- **Determination of the absolute density of solid particles**

The absolute density of the solid particles (ρs) in green clay and sand was determined using the water pycnometer method in accordance with standard NF P94-054.

This method involves measuring the volume occupied by a given mass of solid material in a pycnometer filled with water. The absolute density obtained allows for the characterization of the true density of the solid particles, independent of the voids present in the material.

This property is particularly relevant in calculations of porosity, compactness, and the formulation of composites.

5- **Atterberg Limits**

The Atterberg limits were determined in accordance with standard NF P94-051 to assess the plasticity of undisturbed soil and its behavior in relation to water.

The tests performed include:

- the liquid limit using the Casagrande pan;
- the plastic limit using the roller.

The liquid limit corresponds to the water content separating the liquid state from the plastic state, while the plastic limit represents the water content separating the plastic state from the solid state.

The difference between these two limits allows for the calculation of the plasticity index, an important parameter for assessing the soil's ability to be shaped and compacted.

Figure 6. Casagrande Apparatus for the Atterberg Limits Test.

II.2.2 Characterization of Olive Pomace

Olive pomace serves as the plant-based reinforcing material incorporated into the developed composites. Its physical characterization is necessary to assess its influence on the density, porosity, and thermal and mechanical properties of the developed materials.

1- **Determination of the absolute density of olive pomace**

The absolute density of the solid particles in olive pomace was determined using the graduated cylinder method.

The principle of this method is based on measuring the volume displaced after immersing a known quantity of olive pomace in a liquid. The density is then calculated from the ratio of the dry mass of the material to the displaced volume.

This characterization allows for the evaluation of the effect of plant-based additives on the lightweighting of the composite as well as on its porous structure.

II.3 The composite elaboration

The specimens were prepared by mixing raw earth, sand, water, and predetermined amounts of olive pomace (0%, 10%, 20%, and 30% by weight) until a homogeneous mixture was obtained. The resulting mixture was then placed into standardized moulds measuring 5 × 10 × 20 cm and compacted to ensure good cohesion and a uniform distribution of the constituents. For each of the four formulations, 5 brick specimens were manufactured, yielding a total of 20 specimens designated for testing to ensure statistical reliability. After demoulding, the specimens were placed on a flat surface and stored under ambient conditions, protected from direct sunlight. The drying process was carried out for 28 days to allow the gradual evaporation of water. During this period, the specimens were regularly turned over to promote uniform drying and minimize the formation of shrinkage-induced cracks. At the end of the curing period, the specimens were considered ready for physical characterization and capillary water absorption tests.

Table 1: The different dosages of composite components.

Formulation	(Raw earth + sand) %	Olive pomace %
00 %	100 %	00 %
10 %	90 %	10 %
20 %	80 %	20 %
30 %	70 %	30 %

Figure 7. The prepared composite brick specimens (5 x 10 x 20 cm)

II.4 The composite characterization

II.4.1 Optical Macroscopic Imaging Characterization

The prepared composites were characterized using an optical macroscope to examine their surface morphology and overall structural features. Macroscopic images were acquired in order to evaluate the distribution of olive pomace particles within the earth–sand matrix, identify the presence of pores, cracks, or other visible defects, and assess the homogeneity of the composite.

This technique provides a qualitative understanding of the influence of olive pomace incorporation on the material structure and complements the results obtained from physical and capillary absorption tests.

Figure 8. Optical Microscope Used for Sample Observation (OLYMPUS DP74)

Figure 9. Optical macroscopy image showing the microstructural features of the reference composite containing 0 wt.% olive pomace, observed at a scale of 200 µm.

The reference specimen (0 wt.% olive pomace), exhibits a relatively homogeneous surface morphology, characterized by a cohesive sand-clay matrix with a uniform distribution of constituents and minimal visible defects.

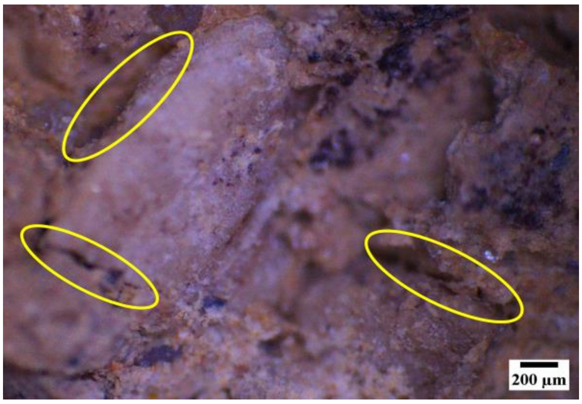

Figure 10. Earth–sand composite containing **10 wt.% olive pomace**, scale: 200 µm

Figure 11. Earth–sand composite containing **20 wt.% olive pomace**, scale: 200 µm

Upon the incorporation of 10 wt.% biomass (Figure 10), the microstructural arrangement begins to alter. The micrograph reveals the onset of minor interfacial defects, primarily manifested as microcracks along the matrix-filler interface.

As the olive pomace content increases to 20 wt.% (Figure 11), a progressive degradation of the interfacial zone is observed. This formulation displays a higher density and greater propagation depth of microcracks within the matrix–filler transition regions compared to the 10% olive pomace reinforced composite.

The 30 wt.% composite (Figure 12) exhibits the most pronounced structural disruption, characterized by significantly larger and more interconnected microcracks compared to the lower dosage formulations (10, 20 wt%).

Figure 12. Earth–sand composite containing **30 wt.% olive pomace**, scale: 200 µm

This progressive accumulation of interfacial microcracks and microstructural heterogeneity at higher biomass contents (20 wt.% and 30 wt.%) suggests a competing dual-mechanism governing the composite's hydraulic performance. While the olive pomace phase is anticipated to act as a physical barrier restricting water uptake, the localized development of matrix–filler defects may introduce preferential capillary pathways that mitigate further systematic reductions in absorption.

II.4.2 Characterization by capillary absorption testing

Capillary absorption tests were conducted in accordance with standard NF EN 772-11. To ensure rigorous repeatability and identical environmental exposure during testing, all four formulations (0%, 10%, 20%, and 30% olive pomace) were placed simultaneously into a single testing container for each test run. The testing was carried out in a temperature-controlled laboratory environment maintained at 20 ± 2°C and a relative humidity of 50 ± 5%.

Figure 13. Capillary absorption test in accordance with standard NF EN 772-11.

To guarantee experimental precision, the weight variations of the specimens during water absorption were recorded using a digital laboratory scale with an accuracy of ± 0.01 g. For the baseline physical characterizations, the water pycnometer used for solid particle density featured an accuracy of ± 0.001 g/cm³.

II.4.3 Statistical Analysis and Repeatability:

To evaluate the statistical significance of olive pomace content on the capillary water absorption coefficient, a one-way Analysis of Variance (ANOVA) was executed across the four experimental groups (0%, 10%, 20%, and 30%olive pomace) with 5 replicate specimens per formulation (total $N = 20$) [14]. Prior to running the parametric variance analysis, the underlying assumptions were verified: data normality within each group was assessed using the Shapiro-Wilk test [15], [16], and homogeneity of variances across groups was verified using Levene's test [17]. The overall magnitude of the effect of biomass addition was quantified using Eta-squared (η^2). To isolate specific localized differences between individual formulations, a post-hoc Tukey's Honestly Significant Difference (HSD) test was performed for pairwise mean comparisons [14]. All statistical computations were evaluated at a significance threshold of $\alpha = 0.05$using Python statistical libraries (scipy.stats and statsmodels). Visual representation of data dispersion and medians was achieved using box plots. Furthermore, it is well-established in statistical literature that the one-way ANOVA F-test is highly robust to minor violations of the normality assumption, particularly when sample sizes are equal across groups and variances are homogeneous [18].

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III. Results and discussion

A. Results of tests to determine the physical properties of the base materials

Table 2: Physical properties summary for raw earth

Test properties	Parameters	Results
Particle Size Distribution (NF P 94-056) (NF P 94-057)	Sand	*48 %*
	Silt	*16 %*
	Clay	*36 %*
Proctor Test (NF P 94-093)	Optimum Moisture Content (OMC)	*24 %*
	Maximum Dry Density (γd_{max})	*1,52 g/cm³*
Absolute density	Solid Particle Density	*2.6 g/cm³*
Dray Bulk density (NF P 94-059)	Bulk density (dry material)	*0.65 g/cm³*
Atterberg Limits (NF P94-051)	Liquid Limit (LL)	*68 %*
	Plastic Limit (PL)	*30.38 %*
	Plasticity Index (PI)	*37.62 %*
Soil Classification	Highly Plastic Clay Soil (*PI >35*)	

Properties:

Analyses show that it is highly plastic (Plasticity Index PI = 37.62%), which gives it excellent workability but requires the addition of sand to limit shrinkage during drying. Its chemical composition reveals the presence of hydrophilic clays such as **kaolinite** and **illite.**

Table 3: Physical properties summary for sand

Test properties	Parameters	Results
Particle Size Distribution (NF P 94-056)	Fine fraction (< 0.08 mm)	*0.75% (Very clean sand)*
	Grain distribution	From *0.2* to *1mm*
Sand equivalent (ES) (NF P 18-598)	ES Visual	*94.5%*
	ES Piston	*97.5%*
Proctor Test (NF P 94-093)	Optimum Moisture Content (W_{opt})	*8 %*
	Maximum Dry Density ($\rho_{d_{max}}$)	*1.98 g/cm3*
	Solid particle density (ρ_s)	*2.70 g/cm3*
Dry bulk density (NF P 94-059)	Bulk density (dry material) (ρ_d)	*1.54 /cm3*

Properties:

It is a very clean material (ES sand equivalent between 94% and 98%) and chemically inert, consisting mainly of quartz. Its absolute density is the highest of the three components (2.70 g/cm³).

B. Capillary Absorption results

The results of the capillary water absorption (water rise) test demonstrate that the incorporation of olive pomace significantly modifies the hygric behavior of earthen bricks.

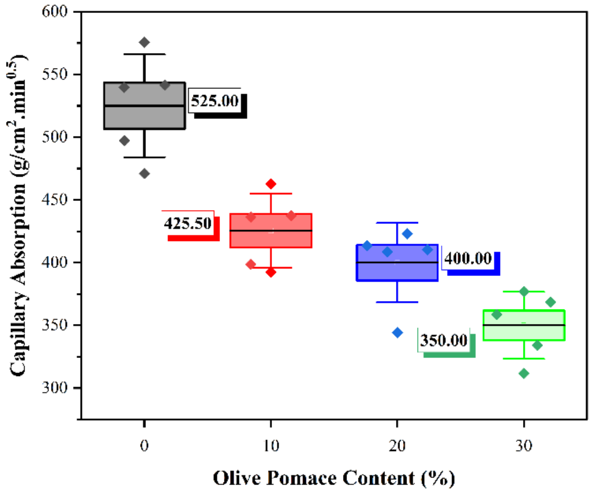

Figure 14. Box Plot for Capillary Absorption Test Results

To transition beyond a purely qualitative assessment of the composite's hygric behavior, a rigorous statistical evaluation was performed on the capillary absorption datasets derived from Figure 14. Prior to conducting the variance analysis, the formal assumptions of parametric testing were verified. Levene's test successfully confirmed the homogeneity of variances across all formulations ($p = 0.853$). While the Shapiro-Wilk test indicated normal data distributions for the 0%, 10%, and 30%formulations ($p > 0.05$), a slight deviation from normality was observed within the 20%formulation ($p = 0.014$). However, given that the study maintains strictly equal sample sizes ($n = 5$) and well-homogenized variances, the one-way ANOVA remains highly robust and mathematically valid for this dataset [18].
The one-way ANOVA revealed a highly significant effect of olive pomace content on the capillary absorption coefficient ($F(3,16) = 25.45, p < 0.001$). The calculated effect size was exceptionally substantial ($\eta^2 = 0.827$), indicating that approximately 82.7%of the entire observed variance in capillary water absorption is directly attributable to the dosage of olive pomace incorporated into the matrix.
To identify the exact thresholds where variations become statistically meaningful, a post-hoc Tukey's HSD test was executed. The results demonstrated that the control reference formulation (0%) exhibited a significantly higher capillary absorption compared to all bio-based modified formulations

($p \leq 0.001$), confirming that adding olive pomace structurally limits water uptake. This aligns with recent findings in bio-based composites where the incorporation of agricultural biomass alters the pore network and reduces capillary suction [19], [20]. When cross-examining the modified variations, no statistically significant difference was observed between the 10%and 20%contents ($p = 0.614$), nor between the 20%and 30%contents ($p = 0.112$). However, the 30%formulation exhibited a significantly lower water absorption coefficient than the 10%formulation ($p = 0.010$). This indicates a clear behavioral threshold: while an initial 10%addition forces an abrupt decline in capillary performance, further sequential steps yield diminishing statistical returns. This statistically positions the 10% to 20% envelope as highly efficient optimal configurations for minimizing moisture transmission without unnecessary material inflation, a phenomenon frequently observed when optimizing the dosage of organic waste in cementitious and earth-based matrices [5], [21], [22].

Experimental results

Measurements carried out on the bricks (5 × 10 × 20 cm) show an overall decreasing trend in water absorption with the addition of olive pomace:

- **Reference formulation (0% olive pomace):**
  It exhibits the highest absorption coefficient, reaching **525 g/cm²·min$^{0.5}$.**
- **Brick with 10% olive pomace:**
  The absorption drops to **425.5 g/cm²·min$^{0.5}$**. In terms of visible water rise height, this formulation shows the most significant reduction, with a decrease of **3.5 cm** compared to the reference sample.
- **Brick with 20% olive pomace:**
  The value continues to decrease, reaching **400 g/cm²·min$^{0.5}$**. However, the measured water rise height slightly increases to **8.0 cm**.
- **Brick with 30% olive pomace:**
  This formulation records the lowest absorption coefficient at **350 g/cm²·min$^{0.5}$.**

Phenomenon analysis

These variations can be explained by modifications in the internal structure of the material:

- **Pore network disruption:**
  The improvement in hygric behavior is attributed to the organic and fibrous nature of olive pomace. These fibers act as physical barriers that disrupt the continuity of the capillary pore network within the clay matrix, thereby slowing down the upward movement of water.
- **Heterogeneity at higher contents:**
  For 20% and 30% dosages, although the overall absorption coefficient decreases, a slight increase in water rise height is observed. This is explained by a more irregular distribution of olive pomace particles, which can locally create larger capillary pathways facilitating water migration.

IV. Conclusions

This study investigated the effect of olive pomace incorporation on the physical properties and capillary water absorption behavior of raw earth-sand composites for sustainable construction. The experimental results and subsequent statistical analysis lead to the following key conclusions:

- **Quantitative Reduction in Water Uptake:** The incorporation of olive pomace significantly improves the hydraulic resistance of the composites. The capillary absorption coefficient decreased progressively from 525 g/cm²·min$^{0.5}$ in the reference formulation (0%) to 350 g/cm²·min$^{0.5}$ in the 30 wt.% formulation.
- **Statistical Significance and Effect Size:** One-way ANOVA confirmed that olive pomace content has a highly significant effect on capillary behavior. Notably, the effect size indicates that 82.7% of the observed variance in water absorption is directly attributable to the dosage of biomass.
- **Identification of an Optimal Threshold:** Post-hoc Tukey HSD tests revealed a clear behavioral threshold. While the initial 10% addition causes an abrupt decline in absorption, sequential increases to 20% and 30% yield diminishing statistical returns. This positions the 10% to 20% envelope as the most efficient optimal configuration for minimizing moisture transmission.
- **Governing Mechanisms:** The reduction in capillary suction is primarily attributed to the disruption of the pore network, where organic fibers act as physical barriers. However, optical macroscopy (Figures 9-12) identified a competing dual-mechanism: at higher dosages (20% and 30%), the localized development of interfacial microcracks creates preferential capillary pathways that mitigate further systematic reductions in absorption.
- **Validation through Literature:** These findings align with recent studies on bio-based composites, confirming that agricultural by-products can effectively modify pore connectivity to enhance moisture durability.

Study Limitations and Future Work: While this study successfully characterizes hydraulic behavior, the increased porosity and interfacial defects at high replacement rates may impact other performance metrics. **Future work** will focus on evaluating the **long-term durability** to ensure these eco-bricks are structurally viable and energy-efficient for practical building applications.

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List of symbols:

ρ_a	*Absolute density of solid particles*
ρ_{max}/γ_{max}	*Maximum dry density*
OMC	*Optimum Moisture Content*
LL	*Liquid Limit*
PL	*Plastic Limit*
PI	*Plasticity Index*
ES	*Sand Equivalent*
$wt.\%$	*Weight Percentage*
F	*F-statistic (from One-way ANOVA)*
p	*Probability value*
η^2	*Eta-squared (measure of effect size)*
α	*Significance threshold*
N	*Total number of specimens*
n	*Sample size per group*
Q_1, Q_3	*First and third quartiles for box plot distribution*

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