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Research Article

Effects of Recycled Expanded Polystyrene Beads on the Mechanical and Physical Properties of Cement-Stabilized Compressed Earth Bricks

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Nowadays, research on environmentally friendly materials has become a significant challenge in the field of civil engineering. In this study, stabilized compressed earth bricks (CEBs) incorporating recycled expanded polystyrene (EPS) beads were studied with the aim of enhancing the development of green constructions. The mass contents of recycled EPS in CEB formulated at a compaction pressure of 5 MPa are 0%, 0.25%, 0.5%, 0.75%, and 1% relative to the mass of the soil, while cement type CEM I 32.5, as a stabilizer, constituted 8% by mass. Characterization was carried out by determining densities, dry and wet compressive strength, flexural strength, total water absorption, and capillarity. Sample properties were found to be strongly influenced by the percentage of recycled EPS. Increasing the EPS aggregate content led to a reduction in compressive strength in both wet and dry conditions. Samples with 0.5% EPS and 8% cement offered better physical and mechanical performance. Samples containing EPS had relatively low water absorption, which would contribute to good durability. These CEBs comply with the wall construction requirements for two-story dwellings. This study also demonstrates the potential use of this recycled material in the construction industry.

1. Introduction

Due to the ever-increasing price of raw materials in Cameroon's construction sector and their environmental impact, earthen construction is currently enjoying renewed interest [1]. Earth has been used in construction since thousands of years because it is abundant and locally available everywhere in the world [1, 2]. Earthen constructions help to reduce potential environmental impact by up to 50% compared to conventional constructions [3, 4]. Unlike cement, concrete, or steel, earth in its natural state can be used as a building material with virtually zero energy expenditure [4]. However, raw earth constructions are feared to be used because of their poor physical performance, lack of durability, and vulnerability to climatic aggressions, particularly rain [5–7]. The stabilizers most commonly used to improve the mechanical, physical, and hygroscopic performance of compressed earth brick (CEB) are cement, lime, and fly ash, with contents generally between 8% and 10% [7–11].

Recent studies have shown that the thermal and hygroscopic properties of bricks can also be improved by incorporating recycled materials such as waste plastics in the form of fibers, aggregates, or melts [12–17]. Indeed, the areas of application of plastics in our daily lives make it difficult to stop using them. One of the plastic wastes incorporated into CEB is polystyrene. Its use is very popular, as it is one of the most widely used materials in the packaging sector, with worldwide waste production of over 15 million metric tons per year [18, 19]. It is known to be a good insulator for residential houses [20]. In the current context, where buildings with good thermal comfort are in demand to reduce energy consumption, their use in building materials could be a good compromise for our planet.

In previous research, the addition of soil, binder, water, and expanded polystyrene (EPS) gave rise to lightened soils, which are used for backfill, retaining walls, underground cavities, and CEB [16, 19, 21–23].

According to several studies, the properties of soils filled with EPS beads are considerably affected by their constituents. A decrease in physical and mechanical properties is noted with increasing EPS aggregate content. In the work of Malahimi et al. [23], polystyrene was incorporated at ratios of 0%–100% depending on a constant volume of raw earth. The results showed decreases in compressive strength (3.24–0.53 MPa). Wang et al. [20] developed a lightweight filler made from Singapore marine clay, ordinary Portland cement, and EPS. The mass ratios of EPS beads to dry clay were 0%, 0.5%, 1%, 2%, and 4%, and the mass ratios of cement to dry clay were 10% and 15%. The results show that increasing the cement content and reducing the EPS content increases the compressive strength of the material. Similarly, Jili et al. [19] characterized the strength of the mixture of expanded polystyrene and Shanghai clay soil. EPS beads were incorporated at ratios of 0%, 0.02%, and 0.03% compared with the soil mass. Four EPS particle sizes were used: 0.5, 1, 3, and 7 mm. The tests showed that compressive strength decreases with increasing EPS bead content and EPS bead size. These results were corroborated by the work of Ali et al. [22], who studied lightened soils consisting of silty soils, expanded polystyrene beads (bead sizes 4, 5, and 6 mm in diameter), and cement (10% and 15%). The findings show that the smaller the EPS bead size (4 mm), the higher the composite strength, while increasing the EPS bead size (5–6 mm) reduces strength and improves ductility. His work has shown that the best compressive strengths are obtained with small EPS beads.

In addition, flexural strength also decreases with increasing EPS bead content [23]. Elastic deformation increases with increasing of EPS bead content but decreases with increasing EPS bead size [19, 22].

In general, the density of CEB containing EPS beads or aggregates ranges from 5 to 18 kN/m^3 [21] and is lighter than natural soils or CEB due to the addition of superlight EPS to the mix. Increasing the EPS bead content reduces the mass density of soils [21]. This leads to a reduction in building mass and improved resistance to seismic forces [16, 24]. An improvement in the thermal comfort of buildings is noted with the incorporation of polystyrene beads, as the thermal conductivity of BTC is reduced [16].

However, the expansion of this construction technique in sub-Saharan Africa, and more specifically in Cameroon, is hampered by the lack of information in the literature on the use of these bricks in these regions. Yet they offer numerous advantages, both in terms of the environment through the recycling of EPS and in terms of energy infrastructure through the reduction of housing energy bills. Moreover, despite a considerable amount of research into lightweight EPS-filled CEB, very little is known about its resistance to climatic stresses and, in particular, its sensitivity to water. As earthen constructions are very often exposed to weathering due to rainwater, capillary rise, and even immersion in the event of flooding, it is important to understand the mechanical behavior of CEB in a wet state in order to know their minimum characteristics under the most unfavorable conditions. This information is very important in order to improve the use of these bricks worldwide, particularly in Cameroon, where the coastal region has a very humid climate with a relative humidity of 85% [25]. The present work therefore involves predicting the mechanical, physical, and hydrophobic behavior of lightweight bricks filled with EPS.

Table 1: Soil properties [17].

Parameters	Results
Optimum water content	16.7%
Liquidity limit	40.64%
Plasticity limit	21.45%
Plasticity index	19.18%
Specific surface area BET (m^2/g)	35.68 ± 0.19
Methylene blue index (g/100 g)	5.89 ± 0.11
Clay	25%
Silt	7%
Fine sand	3%
Medium sand	14%
Coarse sand	51%

2. Materials and Methods

2.1. Materials

2.1.1. Soil. The soil used (Table 1) comes from Douala city, Cameroon, at latitude 4°05′ and longitude 9°74′. It is taken from a depth between 0.5 and 10 m above ground. Once extracted, it is ground and dried in an oven at 105°C for 24 hr. After this time, the mass stabilizes after successive weighing [26]. The basic physical and mechanical properties of the soil are given in Table 1. Its suitability for use in CEB is demonstrated by Ganou et al. [17] (Figure 1).

2.1.2. Recycled EPS. EPS waste is collected from the streets and dumps of Douala (Figure 2). EPS beads are obtained by grinding EPS waste. The granules are spherical in shape and vary in size from 0.5 to 7 mm. They are then sieved to obtain granulometry between 1.6 and 4 mm with a density of 0.20 kN/m^3. Aggregates were used in ratios of 0%, 0.25%, 0.5%, 0.75%, and 1% by the mass of the soil.

2.1.3. Cement and Water. The cement used for reinforcement is ordinary Portland cement of the CEM I-32.5 Dangote type, meeting the specifications outlined in the Cameroonian standard on hydraulic binders NC 234 [27]. The water proportion was determined based on the results of the Proctor test [28].

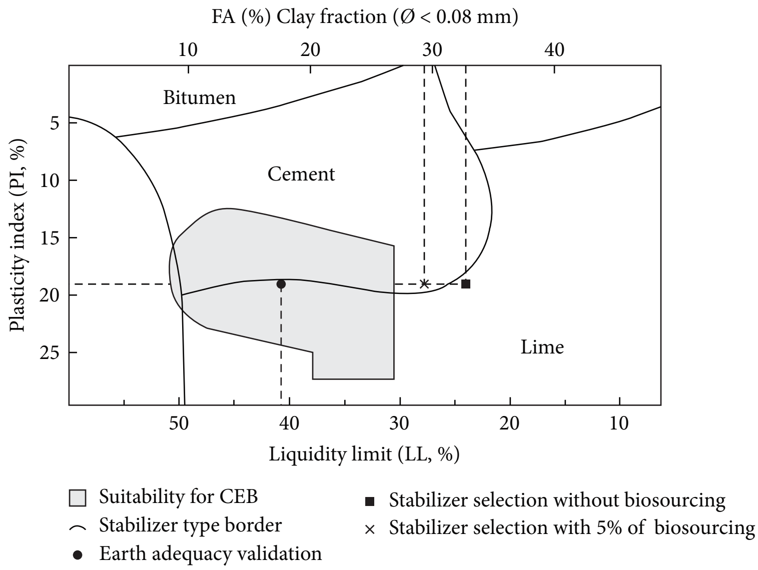


Figure 1: Soil suitability and choice of stabilizer [17].

Figure 2: Polystyrene waste.

Table 2: Proportion of BTC mixtures.

Designation	Composite P_x				
	P_0	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	P_1
Soil (g)	2,000	2,000	2,000	2,000	2,000
Cement (%)	8	8	8	8	8
EPS (%)	0	0.25	0.5	0.75	1
Corresponding EPS volume (%)	0	23.76	47.53	71.29	95.05
Water (%)	15	16	17	18	19
Dosage (kg/m^3)	1,637.82	1,402.37	1,229.18	1,096.45	991.48

2.2. CEB Sample Preparation. The CEBs were manufactured in the civil engineering laboratory at ENSET Douala. The proportions of the various inputs, including soil, cement, EPS beads, and drinking water, were carefully controlled. Five brick formulations were developed (refer to Table 2). The formulations are denoted by names of the form P_x, where x represents the percentage of EPS beads in the samples.

The mixes are made in pans before being introduced into a mold measuring $220 \times 110 \times 40$ mm³. The soil + cement + PSE + water mixture was compacted with a calibrated M&O hydraulic press at a compaction pressure of 5 MPa. Some BTC production steps are shown in Figure 3. The samples were placed under a cover for 28 days. They were then placed in an oven at 60°C for 24 hr before dry testing started [29].

2.3. CEB Characterization. The tests were carried out using an M&O universal mechanical testing machine with calibrated dynamometric rings (part no. 4429 for the compression test

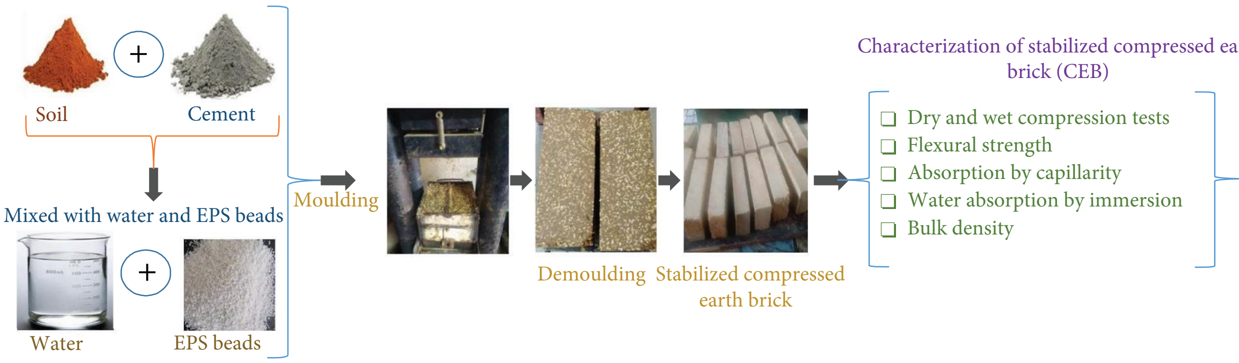


Figure 3: Stabilized compressed earth brick (CEB) elaboration process.

Figure 4: Compression test machine.

Figure 5: Flexural test machine.

and 4433 for the bending test). The bending test was conducted according to EN 12372 [30], and the compression test followed the protocol of NF EN 196-1 [31]. Both tests were performed at an ambient temperature of ~25 ± 2°C and a relative humidity of 70% ± 5%. The specific rate of force application was 2 kN/s.

2.3.1. Dry and Wet Compression Tests. The compressive strength test was carried out on specimens measuring 40 × 40 × 40 mm³. The wet compressive strength test is identical to the dry compressive strength test, with the only difference being that the specimens subjected to this test are first immersed in water for 2 hr. The device for measuring compressive strength is shown in Figure 4. Compressive strength is given by Equation (1):

$$\sigma_c = \frac{F_c}{S}, \quad (1)$$

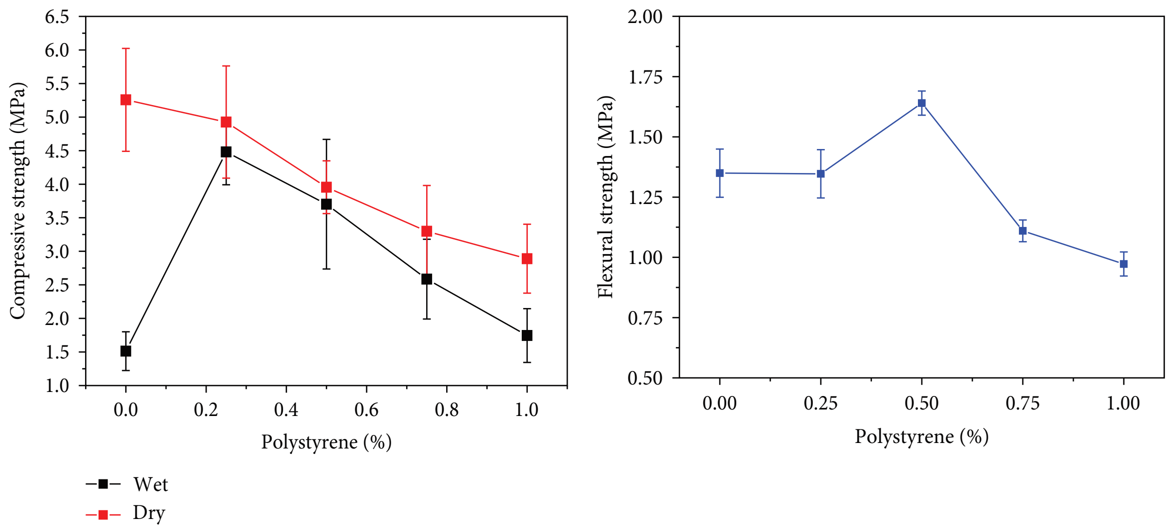
where F_c is the maximum compressive stress (MPa) and S is the specimen cross-sectional area (mm^2).

2.3.2. Flexural Strength. These tests were carried out on samples measuring 220 × 110 × 40 mm³. The materials are considered isotropic, in order to have an identical Young's modulus and bending fracture stress in all directions of the material. The device used to measure the flexural strength is shown in Figure 5. It is determined according to Equation (2):

$$\sigma_f = \frac{3 \times L \times F_f}{2 \times a \times b^2}, \quad (2)$$

where σ_f is the bending strength (MPa), F_f is the brick breaking load in (KN), L is the distance between the two supports (cm), a is the brick width (cm), and b is the brick height (cm).

2.3.3. Absorption by Capillarity. The purpose of the capillary absorption test is to determine the amount of water absorbed by the capillary action of samples. It was carried out in accordance with standard XP P 13-901 [29]. The mass of the sample before immersion is measured (m_0). After 10 min, it was removed from the water, wiped with a dry cloth,



(a) (b)

Figure 6: (a) Dry and wet compressive strengths of CEB as a function of the percentage of EPS beads; (b) flexural strengths of CEB as a function of the percentage of EPS beads.

and weighed to obtain the mass after immersion (m_1). This operation was carried out until the mass of the samples tended to stabilize. The capillary absorption coefficient A is determined by Equation (3):

$$A = \frac{m_1 - m_0}{S \times \sqrt{10}} \times 100, \quad (3)$$

where A is the coefficient of resistance to capillary rise ($g/cm^2 \cdot min^{\frac{1}{2}}$), m_1 is the mass of brick after immersion (g), m_0 is the mass of brick before immersion (g), and S is the surface area of immersed brick in (cm^2).

2.3.4. Water Absorption by Immersion. Water absorption capacity is obtained by completely immersing the sample in water after initially weighing it dry (M_0). After 24 hr of immersion, the sample is removed from the water and reweighed (M_1). The water absorption coefficient W is given by Equation (4):

$$W = \frac{M_1 - M_0}{M_0} \times 100, \quad (4)$$

where W is the total absorption coefficient (%), M_1 is the mass of brick after immersion (g), and M_0 is the mass of brick before immersion (g).

2.3.5. Bulk Density. This is the ratio between the weight and volume of the block. It is determined by using Equation (5):

$$\varphi = \frac{M}{V}, \quad (5)$$

where φ represents the bulk density (kg/m^3), M represents the mass of brick (kg), and V represents the volume of brick (m^3).

3. Results and Discussion

3.1. Compressive and Flexural Strength. The results obtained show a decrease in dry compressive strength with increasing polystyrene bead content compared with the control sample (Figure 6(a)). At contents ranging from 0.25% to 1%, dry compressive strength is reduced by 10.46%–45.06%, respectively, compared with the control. These decreases in mechanical properties have been observed by several authors [16, 23, 32]. Indeed, polystyrene beads create zones of weakness within the blocks, reducing the resistant cross-sectional area of the specimens [23]. In the same figure, we can see that the wet compressive strength of the control sample is lower than that of the samples containing the EPS beads. This suggests that CEB-containing EPS beads is more resistant to water. We observed decreases of the order of 71.5%, 8.9%, 6.3%, 21.6%, and 39.8%, respectively, for 0%, 0.25%, 0.5%, 0.75%, and 1% EPS beads between dry and wet compressive strengths. According to the requirements defined by ASTM E2392M-10 (2 MPa for dry compressive strength and 1 MPa for wet compressive strength) [33], bricks containing up to 1% recycled EPS could be used in construction, as they have a dry compressive strength of 2.88 MPa and a wet compressive strength of 1.51 MPa. The higher the EPS bead content, the easier it is to recycle polystyrene for construction projects and also to obtain a less dense, more porous CEB that guarantees better thermal performance.

For flexural strength, with the addition of EPS up to 0.5%, there is an 8.2% increase in flexural strength compared to the control BTC. Figure 6(b) shows that the addition of EPS beads above 0.5% leads to a reduction in brick flexural strength. The flexural strength of the mixture with 1% EPS beads is 27.61% lower than the control, dropping from 1.34 to <1 MPa. In fact, the increase in EPS beads favored the formation of voids in the composite, causing a reduction in flexural strength. This effect can be explained by the low

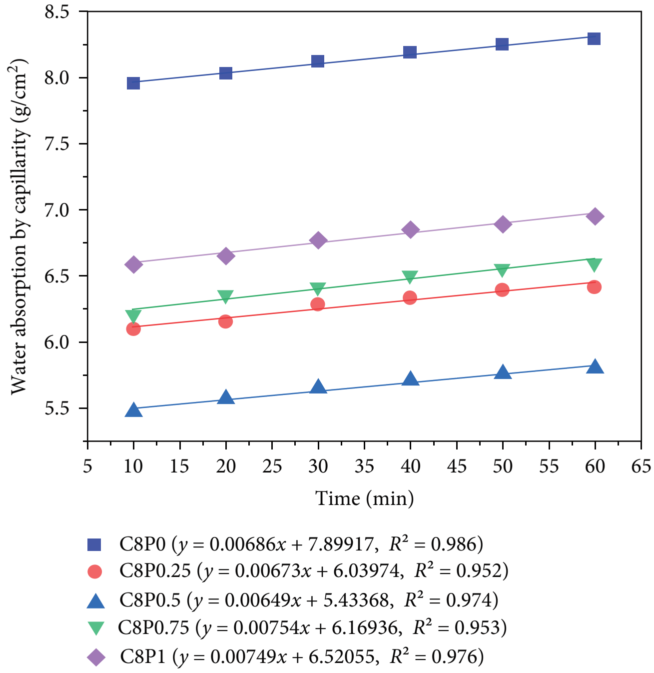


Figure 7: Water absorption by capillary action of CEB as a function of time.

density and the voids created by the EPS beads during mixing [23].

3.2. Absorption by Capillarity. Capillary absorption depends on the variation in EPS bead content (Figure 7). Its measurement was used to determine the capillary diffusion coefficient ($g/cm^2 \cdot min^{\frac{1}{2}}$). Figure 7 shows linear correlations between capillary water uptake and time (1 hr time range) for stabilized CEB loaded with EPS beads and simply stabilized CEB. Between 0% and 0.5%, after 1 hr capillarity drops, respectively, from 8.24% to 5.80%. For EPS bead contents above 0.5%, capillarity increases up to 6.91% with 1% EPS fillers. For EPS bead contents less than 0.5%, the optimum proportions of soil, EPS beads, and cement create a mixture with a minimum of voids, which can explain the decrease in capillarity. For EPS bead contents above 0.5%, the bond between the particles and the matrix is weaker, creating voids in the bricks and increasing the capillarity coefficient. The highest capillary absorption value after 1 hr is $8.24\,g/cm^2 \cdot min^{\frac{1}{2}}$ for control CEB (Figure 7). After 20 min, the formulations tend to stabilize. These values enable us to classify these CEBs as low-capillary bricks with a capillarity coefficient of less than 20% [29].

3.3. Water Absorption. The water absorption capacity of the samples was investigated. In the work of Veiseh and Yousefi [16], water absorption decreased with increasing EPS content in clay bricks. In our work (Figure 8), we observed a decrease in the water absorption rate from 9.86% to 6.96% for 0% and 0.5% EPS, respectively, which could be explained by a good interaction between EPS and earth at low EPS percentages, resulting in a reduction in brick porosity. However, for EPS bead contents above 0.5%, water absorption increases up to 9.23% with 1% fillers. Water is absorbed in stabilized CEB due to the migration of water into the capillary pores of the bricks. In fact, the presence of a high proportion of EPS beads increases the number of pores and voids in the bricks [23], leading to increased water migration into the CEB. Indeed, several studies have shown that the incorporation of plastic aggregates in bricks leads to an increase in the water absorption rate of the bricks [23, 34–37]. This increase would be due to the inclusion of heterogeneities by the plastic, which would probably make the materials more porous. In other words, when EPS aggregate is incorporated into the mix (with a grain size larger than that of the initial composite), it creates an appropriate porosity that is different from that created by the earth, since its shape is spherical and voluminous.

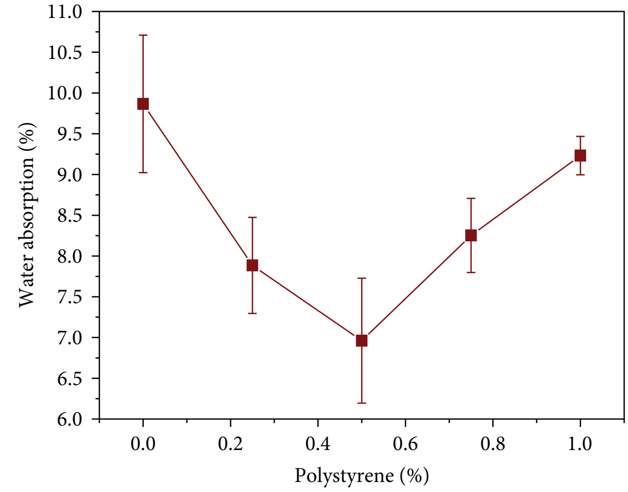


Figure 8: Relationship between percentage water absorption and EPS bead content.

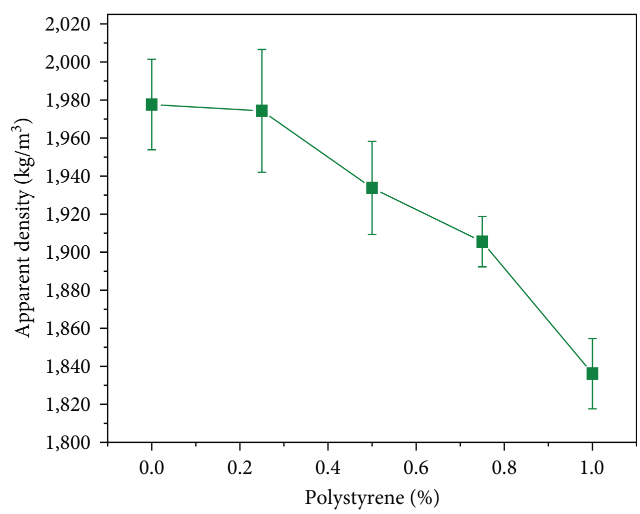


Figure 9: Bulk density of CEB samples as a function of EPS bead content.

3.4. Apparent Density. The apparent density of the samples is shown in Figure 9. Density values range from 1,836 to 1,977 kg/m^3. Sample density decreases as the percentage of

EPS increases. These decreases have been observed by several authors [16, 23, 38, 39]. The low density of the EPS beads contributes to the decrease in sample density. The reduction in density is explained by the incorporation of ultralight polystyrene beads acting as voids created inside the bricks [23].

4. Conclusions

In this study, the effects of incorporating EPS beads into stabilized CEB were highlighted.

(1) We noted the reduction in compressive strength with increasing levels of EPS beads in the formulations, since EPS beads reduce the resistant surface area of a section. Also, wet compressive strength is better for samples with EPS beads, and the highest value obtained is 4.4 MPa for CEB with 0.25% EPS beads.
(2) The bulk densities of CEB decrease with increasing EPS beads. The decrease in the compressive strength of bricks can be explained by the reduction in apparent densities due to the internal structure of the samples.
(3) Total water absorption and capillary absorption of the samples are lower than those of the control sample, with the lowest values obtained for samples with 0.5% EPS beads at 6.96% and 5.47%, respectively.
(4) The addition of EPS beads at a rate of less than 0.5% to the mix considerably reduces the ability of CEB to absorb water, making it more durable.

This work proposes a method for recycling EPS waste in an ecological and sustainable way. However, physicochemical characterizations integrating thermal comfort and durability still need to be carried out. The reuse performance of the composites obtained will also be highlighted in our future work.

Data Availability

All data used in this article are freely available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Géraldine Gouafo Kougoum and Ulrich Giresse Tatchum Defo. The first draft of the manuscript was written by Géraldine Gouafo Kougoum, and all authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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