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The utilization of pulverized waste tire rubber in a soil–cement composite for sustainable compressed earth brick production

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Abstract

This study examined the suitability of blending waste tires with cement in indigenous soil for producing compressed earth bricks (CEB) to achieve a sustainable environment. CEB was produced with clay soil and a combination of cement at 5 and 10% levels with varying dosages of pulverized waste tire at 0, 2.5, 5, 7.5, and 10% mixture. Classification tests were conducted to determine engineering properties such as the particle size distribution, Atterberg limit, specific gravity, optimum moisture and unit weight of the soil. The physical properties of the pulverized tire were evaluated. Moreover, density, water absorption, and compressive strength were determined for hardened CEB samples produced from mixtures of soil and various proportions of blended cement and pulverized waste tire materials. The classification results showed that the soil was silty clay of low plasticity. The density of the CEB samples was observed to increase slightly with the addition of blended cement-tire residue. Furthermore, a considerable improvement in the compressive strength development of the CEB was observed; however, compared with those of the control, the peak compressive strength of the CEB samples was greater when the soil was stabilized with 7.5% pulverized waste tire material and 10% cement. A decrease in the water absorption capacity of CEB was observed with an increase in the amount of pulverized waste tire and cement in the soil mixture. The response models corroborate the experimental findings indicating that amount of waste tire rubber residue and cement had significant effects on the CEB performance. This study ensure the beneficial recycling of waste tires blended with cement in soil for making medium-strength CEB to achieve sustainable, resilient masonry construction applications.

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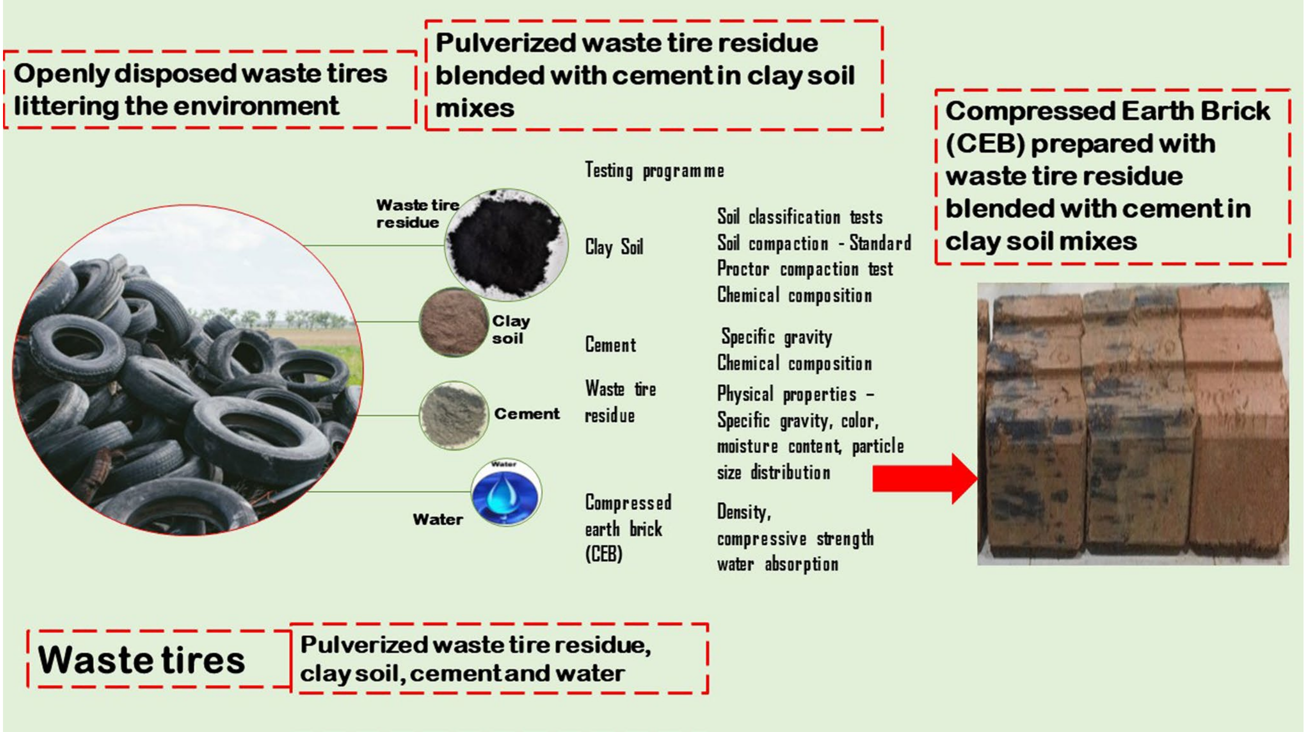
Graphical Abstract



Highlights

- Incorporation of waste tire rubber residue blended with cement in silty clay soil for making medium-strength CEB
- Addition of blended waste tire rubber residue-cement in silty clay soil improved strength and reduce the water intake rate of CEB
- The blended waste tire rubber residue-cement can be used at optimum of 6% waste tire residue, 7.5% cement in clay soil composite mixes for making medium-strength CEB

Keywords Compressed earth brick · Recycled waste tire · Masonry · Compressive strength · Water absorption · Sustainable construction

1 Introduction

In recent times, the generation of solid waste has continued to increase tremendously, largely due to urbanization, population growth, modernization, and rapid evolution in living standards [1]. Solid waste generation is the unavoidable result of all processes from the various households and industries in any society [2]. These processes include product manufacturing, raw material extraction, food processing, consumption, agricultural processes, construction and demolition activities, and household waste. Hence, a large volume of solid waste, both industrial and municipal waste, is generated annually [3]. A World Bank report from 2017 stated that, as of 2016, approximately 4.01 billion tons of solid waste were generated globally in many urban cities and regions, and it was estimated that by the year 2050, the amount of solid waste would increase by 70% [4]. Moreover, the United Nations Environmental Programme (UNEP) posited in their global outlook report that the global municipal solid waste generation is predicted to grow from 2.1 billion tons in 2023 to 3.8 billion tons by 2050 [5].

Currently, the rate of material usage is so high that urgent actions are needed to manage the impact of these consequences on environmental quality and societal health [6]. This approach is necessary, especially in developing countries with modest urban communities that lack an effective strategy for sustainable solid waste management practices to handle generated solid waste disposal [7]. Moreover, such communities usually indiscriminately dispose of their waste at open dump sites or poorly managed landfills, which results in environmental pollution that endangers the community's well-being. Additionally, many of these developing countries had very limited and weak infrastructure for waste recycling or lacked the necessary plans for handling recyclable waste materials [7]. There are various types of solid waste, but discarded rubber tires are perhaps among the most environmentally unfriendly solid wastes. Approximately 1.5 billion new tires are estimated to be constantly manufactured globally, and approximately two-thirds of these tires reach their End-of-Life (ELTs) [8]. ELTs refer to tires that have reached their serviceable lifecycle and can no longer be used for their major function; hence, they are considered waste. Many industrialized nations, such as European Union (EU) nations, Japan, China and the United States of America, have developed sustainable processes to reduce their ELT; however, many developing countries, such as some countries in Africa, still struggle with handling discarded tires, and large portions are mostly indiscriminately disposed of in dump sites, creating nuisance to the environment [9]. Hence, there is a need to find a sustainable, innovative action that allows waste tires to be recycled or reused in a manner that mitigates or eliminates their negative effects on the environment.

On the other hand, the construction industry is regarded as a polluting industry due to its activities and use of raw materials, and experts are consistently seeking alternative materials with low environmental impact. Many studies have investigated ways of reducing the impact of construction activities on the environment. The feasible use of combined waste plastic with ceramic waste as alternative aggregates to conventional aggregates for producing an eco-friendly self-compacting concrete for structural element applications was recommended by [10]. The possible utilization of waste floor tile as fine aggregate in flowable sand concrete was studied and findings indicated that flowable sand concrete mixes produced with floor tile waste performed better than the conventional one in terms of materials cost reduction and limiting environmental impact [11]. The use of organic wastes with particular focus on vegetable waste from the olive processing industry (olive core) to develop energy saving and insulating self-compacting mortar was studied, and results showed that the discarded olive core material can be used to develop various types of nonstructural members with good insulating properties [12]. In another study, spent coffee grounds was used as alternative bio-aggregates for sand replacement in making new concrete, and findings showed that thermally insulating eco-friendly structural concrete elements can be produced with spent coffee grounds used as sand replacement [13]. Waste plastic in the form of polyethylene-terephthalate as fiber and low-density polyethylene plastic as powder was studied as effective constituents in the making of cement mortar composite [14]. In a recent study, seashell powder combined with industrial granite waste was suggested as alternative material in development of new green flowable sand concrete of low production cost, reduce carbon emission and waste, and preservation of raw resources [15].

The use of earthen material is being studied as a possible alternative material, and one of the approaches to using earth as a material for construction is for making compressed earth blocks or bricks (CEB) [16]. CEB formed mainly with earth, water and stabilizers (such as sand, lime, cement, and fiber) are usually deployed for masonry work in buildings [17]. CEB is an economic construction technique with good resistance and durability properties compared to those built with adobe or other traditional materials [18]. The production stages of CEB create very few waste and required less carbon emission and embodied energy, and cause no direct environmental pollution during the whole life cycle [19]. Some of the advantages of using CEB is that the material is locally sourced indigenously thereby reducing transportation cost and provision of low-cost and affordable housing. Other advantages include improvement of the local economy rather than importing building materials and low skilled labour requirement and faster and easier construction process [19].

In addition, CEBs made from the earth can also be utilized for load-bearing walls [20]. Furthermore, some studies have proposed the use of modified indigenous earthen material for making CEBs. The modified indigenous earthen material refers to the application of indigenous technologies with locally available earthen materials in CEB production [21, 22]. Examples of these indigenous technologies include adobe bricks, wattle, cob, rammed earth, and daub construction. Soil modification or stabilization of CEB are particularly important for enhancing the physical features of the soil, improving the strength and durability properties, and reducing shrinkage cracks in the CEB. Some of the sources of this stabilizer include plants (sap, fibers), animals (hair, manure) and minerals (lime and cement) [23]. However, in recent times, experts and researchers have been considering substances from agricultural and industrial wastes to improve earth materials [24]. Examples of such materials studied by experts and researchers include aluminum dross [25], waste plastic in fiber form [26, 27], marble waste [28], cassava peels [29], waste glass powder [30] and many more. However, very recently, waste rubber tires have been investigated for their suitability in CEB applications to help solve the menace posed by scrap tires.

Scrap tires can be recycled and blended with soil in various forms, such as powders, shreds, fibers, and chips. Scrap rubber tire fiber combined with lime and glass fiber was utilized to improve the properties of CEB and findings showed that the scrap tire rubber fiber evidently affects the mechanical properties, ductility and deformability of the CEB [31]. Similarly, another study recommended that crushed rubber tires combined with lime to can be utilized as a stabilizing material in clay soil [32]. A study suggested the incorporation of waste rubber tire powder can be used for improving cement-clay composites which can be deployed in structural and non-load-bearing applications [33]. Meanwhile, blending rubber tires with clay soil causes a decrease in the unconfined compressive strength (UCS) and stiffness of the clay soil [34]. However, few studies have shown that incorporating rubber tires in soil slightly improves the stiffness and strength properties of the soil [35, 36]. Moreover, the utilization of cemented earthen is considerably increasing to improve the soil quality for making clay composites. Blending cement in low quantities with weak soil increases its strength [37]. Grade 53 cement type and shredded tire chips from waste rubber tires was used to stabilized a locally sourced lithomargic soil and findings showed an increased in the engineering properties such as the unconfined compressive strength, frictional angle and California bearing ratio (CBR) of the modified soil [38].

However, to the best of the authors' knowledge, the use of blended waste tire rubber residue with cement in indigenous earth soil to make moderate strength CEB for structural applications has yet to be widely investigated. Therefore, this study aimed to investigate the suitability of using waste tire rubber residue blended with cement in earth soil sourced locally to produce CEB of medium strength for structural applications. The specific purpose of this study was to evaluate the physical properties of the utilized materials, including establishing the engineering properties of the soil for adequate soil classification. In addition, the effect of blended tire residue-cement on the density, strength, and water absorption resistance of the produced CEB was investigated. Furthermore, the response surface was used to develop predictive models that establish the optimum percentage content of cement and waste tire rubber in the soil mixtures to optimize the strength and water absorption performance of the CEB. It was posited that using waste tire rubber residue in CEB will contribute significantly to reducing the burden of nuisance and contamination caused by these scrap tyres on the environment.

2 Experimental programme

2.1 Materials

In this research, the materials used included soil, cement, and pulverized waste tire rubber residue. The soil was obtained from a location in Agbara town, Ogun State, Nigeria, which has a large deposit of soil quarry for making earth bricks. The soil (Fig. 1a) was obtained as a disturbed sample from the location and was subsequently conveyed to the laboratory, where it was openly desiccated, and care was taken to ensure that the lump soil was properly crushed, as suggested by [27]. Selected geotechnical properties of the soil were examined, which included several index properties and consistency limit tests of the soil in accordance with relevant standards. The soil color was observed visually, and the particle size

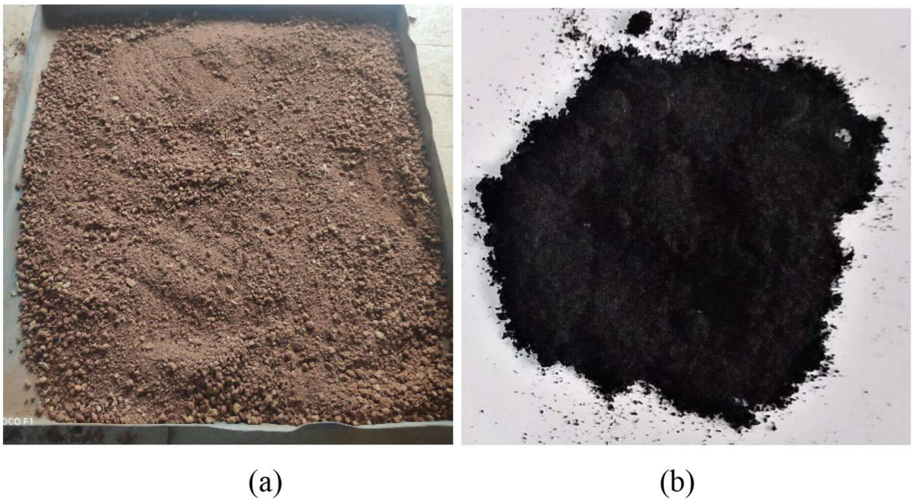

(a) (b)

Fig. 1 **a** Soil and **b** waste tire rubber residue distribution and specific gravity were determined for the soil samples in accordance with [39] and [40], respectively. The consistency limit tests, otherwise referred to as Atterberg limit tests of the soil, were carried out following the guidelines of the [41] standard. Moreover, the optimum moisture content (*OMC*) and maximum dry density (M_{dd}) of the soil were established using the standard Proctor compaction test carried out in accordance with [42]. The chemical composition of the soil sample was determined using X-ray fluorescence.

The cement used is type 1 grade 42.5 Portland cement for a broad purpose, which was bought within Ota metropolis, Ogun state, Nigeria. The cement conforms to [43, 44] standards. The chemical content of the cement was determined using X-ray fluorescence. The pulverized waste tire was obtained from the recycling of unused and discarded tires collected from dump sites at various locations within the Ota metropolis, Ogun State, Nigeria. After collection, the discarded tyres were carefully washed with water to remove any contamination, air dried, shredded and further broken down into granules using an industrial crushing mill. Figure 1b depicts the resulting light–dark pulverized tire powder. The specific gravity and particle size distribution of the pulverized waste tire material was determined. Table 1 lists the various testing programs used on the various materials, which included soil, waste tire powder, and compressed earth brick samples made with mixtures of soil, pulverized waste tire powder and cement materials. Meanwhile, the chemical element composition of crushed tire powder based on energy-dispersive X-ray spectroscopy (EDX) revealed oxygen (8–6%), carbon (88.1%), silicon (0–3%), aluminum (0.05%), zinc (1–8%), sulphur (1–1%), and magnesium (0.11%) [33]. All the material preparation and testing were conducted at the geotechnical and materials laboratory of the Department of Civil Engineering, Covenant University, Ota.

2.2 Materials, sample preparation and testing programme

The compressed earth bricks with dimensions of 240 × 220 and 110 mm in depth were produced at the optimum moisture content with a combination of soil and cement (5 and 10% of soil mass) with the incorporation of varying amounts of pulverized waste tire rubber in residue form at 0, 2.5, 5, 7.5, and 10% proportioned by the mass of cement. The mixtures were proportioned and mixed under dry conditions, and water was gradually incorporated until the optimum water content was attained to form a homogenous clay puddle with sufficient workability. The production of compressed earth brick (CEB) samples was carried out using a hydraulic compacting machine to form CEB samples. Table 2 shows the percentage mixing proportions of the materials used in the preparation of the CEB samples. Overall, 30 mixtures were prepared with a combination of the various materials at a constant optimum water content for preparing the CEB samples.

2.3 Compression strength test

After production of the compressed earth bricks (CEB), the samples were left open and placed on a higher platform above the ground at room temperature to allow the earth brick samples to cure and gain sufficient strength for 28 days, as shown in Fig. 2, after which the samples were subjected to a compression strength test using a compressive crushing machine (Fig. 2). The tests were performed in duplicate, and the mean values were reported. The recorded compressive strength of the CEB samples was determined using Eq. (1).

$$Compressive\ strength\ (CS) = \frac{Crushing\ load\ on\ the\ sample}{Sample\ Area} \tag{1}$$

2.4 Water absorption test

Furthermore, the capacity of a CEB sample to take in water is a key factor that influences both its strength and durability properties. Consequently, the water absorption capacity of the produced CEB samples was examined after 28 days, upon which the CEB samples are expected to have fully gained strength. The CEB samples were completely submerged in water for 24 h before the samples were weighed and placed in an oven to dry to an unchanging mass at a steady temperature of 115 °C. The water absorption of the CEB was then evaluated by calculating the reduction in the mass of wet samples of the compressed earth brick (M_2) and dry samples (M_1). Thus, the water absorption of CEB is determined using Eq. (2):

$$Water\ absoprtion\ (\%) = \frac{M_2 - M_1}{M_1} \times 100 \tag{2}$$

Table 1 Summary of tests on materials and brick samples

Test description		Remarks
Soil	Soil classification—Index tests and consistency limits test [39, 41]	Tests on the soil sample to determine the natural soil index—particle size distribution, moisture content, Atterberg's limit, color and specific gravity
	Soil compaction—Standard Proctor compaction test [42]	Soil compaction to establish the optimum moisture and maximum dry unit weight of the soil
Cement	Physical properties—specific gravity, Chemical composition [43, 44]	Physical and chemical characterization of the cement and tire materials
Waste tire residue	Physical properties—specific gravity, color, moisture content, particle size distribution [39, 40]	
Compressed earth brick (CEB)	Mechanical properties—Density, compressive strength and water absorption [45]	Tests on hardened CEB to determine the hardened bulk density, strength, water absorption tendency

Table 2 Mixture batching of the compressed earth brick in relation to the soil weight

Mixture code	Soil (%)	Cement (%)*	Waste tyre rubber residue (%)**	Water content (%)
CEB1	100	0	0	17.5
CEB2	100	0	2.5	17.5
CEB3	100	0	5	17.5
CEB4	100	0	7.5	17.5
CEB5	100	0	10	17.7
CEB6	100	5	0	17.5
CEB7	100	10	0	17.5
CEB8	100	10	2.5	17.5
CEB9	100	10	5.0	17.5
CEB10	100	10	7.5	17.5
CEB11	100	10	10	17.5
CEB12	100	5	2.5	17.5
CEB13	100	5	5.0	17.5
CEB14	100	5	7.5	17.5
CEB15	100	5	10	17.5

*Proportion of cement relative to the dry weight of the soil

**Proportion of tire rubber residue relative to the cement weight

Fig. 2 Compressed earth brick (CEB) sample and testing

3 Results and discussion

3.1 Physical properties—soil and waste tire

Table 3 shows a summary of the recorded physical properties of the soil and of the pulverized tire powder materials. The soil color is reddish brown, and based on the recorded values of the consistency index tests of the soil, which are the liquid limit (L_L-41.6%), plastic limit (P_L-19.6%) and plasticity index (PI-22%), the soil is classified as CL, which is a silty clay soil of low plasticity according to the Unified Soil Classification system (USCS). Moreover, the chemical composition of the soil, as shown in Table 4, reveals that the soil contains a sufficient amount of silica compound (67%) and is also rich in alumina (12%), calcium oxide (2%), iron (6%), potassium oxide (1.8%) and magnesium oxide (1.52%), and the likely mineralogical phase of the soil includes quartz, smectite, and illite. The specific gravity of the soil is 2.57, while Fig. 3 shows that approximately 40% of the soil particles were retained on the 0.075 mm sieve opening. Hence, the soil has suitable features for making CEB [46]. The observed specific gravity and water absorption values for the pulverized waste tire are 0.42 and 0%, indicating that the material is lightweight and does not absorb

Table 3 Physical properties of the soil, cement and pulverized waste tire

Properties	Soil	Waste tire residue	Cement
Plastic limit, P_L (%)	19.6	–	
Liquid limit, L_L (%)	41.6	–	
Plasticity index, PI (%)	22.0	–	
Specific gravity	2.57	0.42	3.15
Color	Reddish brown	Light dark	Light gray
Percent passing no. 200 (0.075 mm) sieve	45	0.05	
USCS Classification	CL	–	
Moisture content (Optimum), %	17.5	–	
Dry unit weight (Maximum), kg/m^3	1722	–	

Table 4 Chemical composition of the cement and soil

	Cement type I	Soil
Silicon oxide, SiO_2 (%)	15.40	67.40
Aluminum oxide, Al_2O_3 (%)	4.14	12.70
Iron oxide, Fe_2O_3 (%)	3.19	6.15
Calcium oxide, CaO (%)	57.00	1.50
Magnesium oxide, MgO (%)	2.44	1.52
Sulphur trioxide, SO_3 (%)	1.59	–
Sodium oxide, Na_2O (%)	0.04	1.40
Potassium oxide, K_2O (%)	0.21	1.81
Titanium dioxide, TiO_2 (%)	0.21	
Phosphorus pentoxide, P_2O_5 (%)	0.28	
Manganese (III) oxide, Mn_2O_3 (%)	0.04	
Dichromium trioxide, Cr_2O_3 (%)	0.02	
Loss on ignition, LOI (%)	15.59	7.50

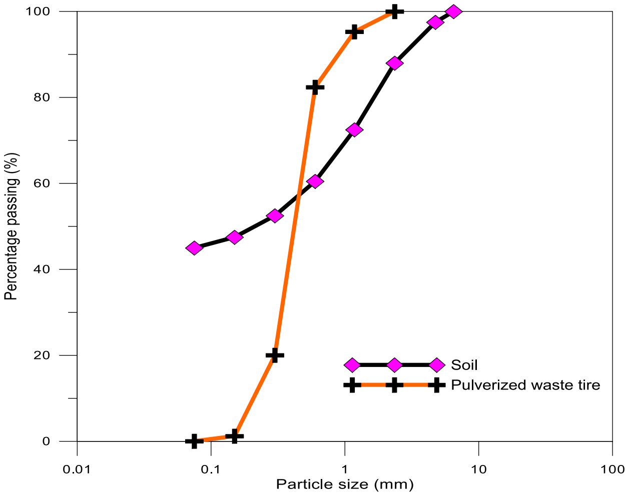


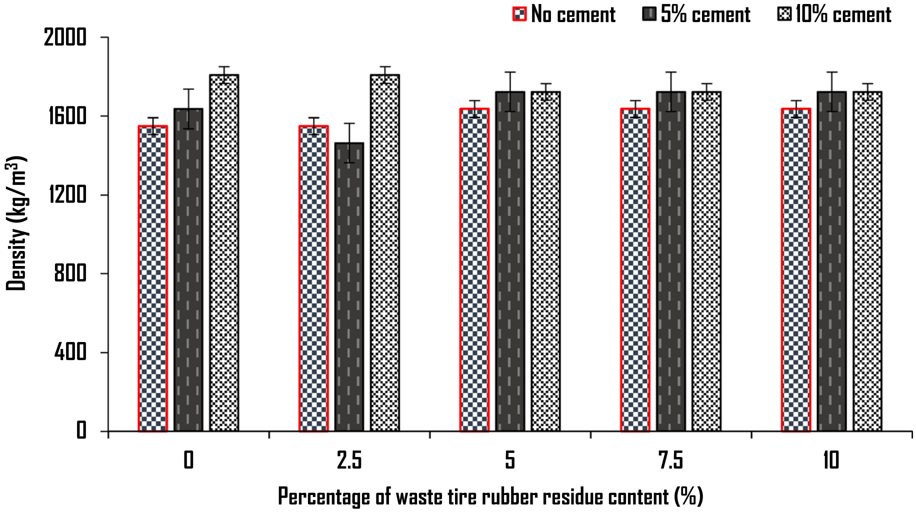
Fig. 3 Particle size distributions for soil and pulverized waste tire

water. Figure 3 shows the results of the sieve analysis of the waste tire materials. The recorded optimum moisture content for the soil was 17.5%, and the recorded highest dry density was 1722 kg/m^3.

3.2 Effect of blended cement–waste tire residue on the density of CEB

Figure 4 shows the average values for the density of the reference CEB samples and those produced with waste tire rubber residue and blended cement-waste tire rubber residue. The average density of the reference CEB is 1549.59 kg/

Fig. 4 Density of CEB samples



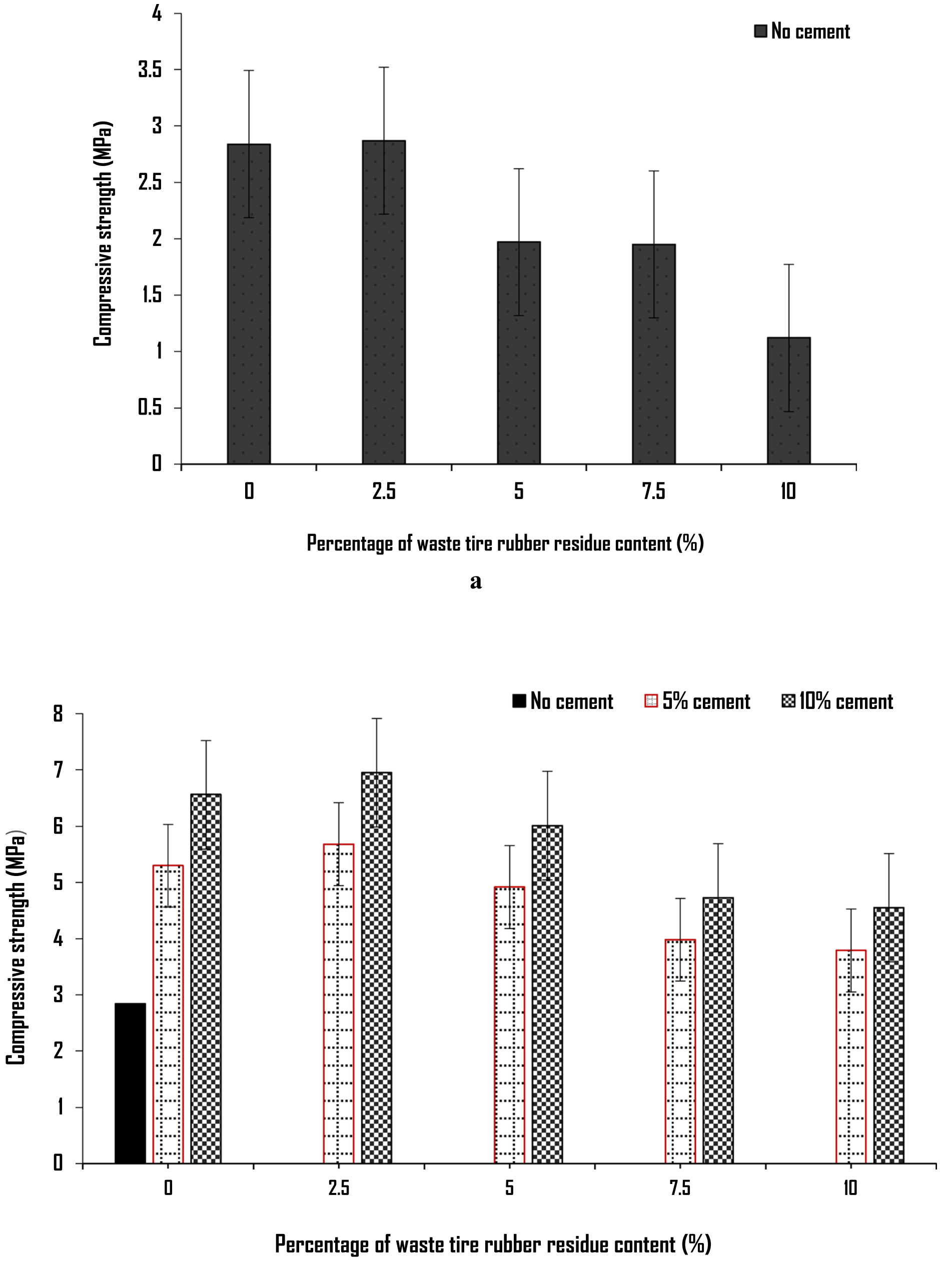
m^3, and that of the CEB containing waste tire crumbs is 1614.15 kg/m^3. The average density values for the reference CEB with the addition of cement are 1637.65 kg/m^3 (5%) and 1807.85 kg/m^3 (10%), while those for the CEB containing waste tire crumbs are 1657.20 kg/m^3 and 1743.28 kg/m^3 at 5% and 10% cement, respectively. The results revealed that the integration of cement-tire crumb materials into the soil mixes slightly increased the CEB density despite the varied compacting pressure and batching compositions. These results are closely comparable to the reported findings of [47] on compressed stabilized earth bricks (CSEBs) made with laterite soil, sand and cement.

3.3 Effect of blended cement–waste tire rubber residue on the compressive strength of CEB

The compressive strength is a vital factor in determining the strength performance of CEB for structural purposes. The ability of a compressed earth brick to carry the load imposed on it is one of its main mechanical properties, and most often, these properties are influenced by soil type, curing conditions, molding pressure and other materials such as fibers incorporated in the soil mixtures [48]. In this study, the variations in the compressive strength development of the CEB samples containing only waste tire residue and CEB samples produced with blended cement-waste tire residue are presented in Fig. 5a and 5b, respectively, for the various replacement levels relative to the control.

Figure 5a depicts the variation in the compressive strength of the CEB containing varying percentages of waste tire residue. As shown in the figure, a slight increase in compressive strength was observed with an initial increase in the amount of waste tire rubber residue in the soil mixture used to make the CEB. However, the compressive strength began to decrease as the waste tire rubber residue content increased. It is possible that the initial incorporation of limited amounts of pulverized waste tire residue causes the CEB to be denser and less porous. However, the compressive strengths recorded for all the CEB ranged from 1.12 MPa to 2.84 MPa, with some meeting the 1 MPa and 2 MPa recommended by [45] and [46] standards, respectively. However, none of these tests achieved the minimum pressure of 3 MPa recommended by [48]. These results are very similar to the findings of [22, 27], who linked the initial increase in compressive strength of the produced CEB with shredded plastic fibers to the surface adhesion between the soil matrix and fibers. Additionally, findings are also similar findings of [29, 49], who uses combined coal ash and cassava peels and hemp fibers, respectively. The studies reported a decrease in compressive strength with increasing cassava peel and fiber content, which was linked to increased porosity in the CEB samples. The highest compressive strength value of 2.89 MPa was recorded for CEB containing 2.5% waste tire residue, which represents an approximately 5% increase compared to the control. Moreover, the observed decrease in compressive strength as the waste tire rubber residue content increased could be attributed to a possible gradual decrease in adhesion between the soil matrix and waste tire rubber residue material. This implies that increasing the amount of waste tire rubber residue beyond 10% could have a negative impact on the strength of CEB.

Figure 5b shows the development of the compressive strength of the CEB as a function of varying amounts of blended cement–waste tire rubber residue in the soil mixture. The figure illustrates the effect of incorporating cement at 5 and 10% with waste tire crumb residue and soil mixes on the strength development of the CEB. The recorded results indicate that the compressive strength of CEB improves significantly with increasing cement content for every proportion



a

b

Fig. 5 **a** Effect of waste tire residue on the compressive strength of the CEB samples. **b** Effect of blended cement-waste tire residue on the compressive strength of the CEB samples

of waste tire rubber residue. The increase in the compressive strength of the CEB produced by the addition of blended cement–waste tire rubber residue could be attributed to improved surface adhesion between the soil matrix and waste tire rubber residue, facilitated by the incorporation of a binding agent (cement), which results in more densely packed CEB composites through compaction. At 5% cement content, the compressive strength for the control and CEB containing 2.5, 5, 7.5 and 10% waste tire crumb residue increases from 2.84 MPa, 2.89 MPa, 1.90 MPa, 1.75 MPa and 1.12 MPa to 5.3 MPa, 5.68 MPa, 4.92 MPa, 3.98 MPa and 3.79 MPa, respectively. This increase in the compressive strength is greater than 141.5%. When the cement content further increased from 5 to 10%, a further increase in the compressive strength of the CEB was observed to be 6.56 MPa (0), 6.95 MPa (2.5%), 6.01 MPa (4.73) and 4.55 MPa (10%). This increase in compressive strength is an average of approximately 21.0%. The highest compressive strength values of 5.68 MPa and 6.95 MPa were recorded for CEB containing 2.5% waste tire residue for both 5% and 10% cement content, respectively, compared to those of the control. The increase in compressive strength recorded could be a result of the calcium silicate hydrate gel (CSH) that formed in the soil composite mixes due to the hydration process, and this gel fills the CEB pores, resulting in improved adhesion and bonding between the soil particles and waste tire rubber residues, similar to the findings of [22, 33, 50–52]. Moreover, despite the increase in strength due to cement addition, a decrease in compressive strength was still observed with an increasing amount of waste tire rubber residue in the CEB. This signifies that increasing the amount of waste tire rubber residue in CEB could have a negative impact on the strength development of CEB. However, it should be stated that the compressive strength values recorded for all the CEBs stabilized with blended cement-waste tire rubber residue meet the recommended minimum compressive strength requirements of 1 MPa, 2 MPa and 3 MPa suggested by [45, 46, 48] standards, respectively.

3.4 Water absorption

Estimating the water intake properties of compressed earth bricks used in building construction is highly important because of their low resistance to moisture absorption, which has a destructive effect on earth bricks, hence affecting their long-term performance. The absorption capacity of stabilized CEBs is a typical indication of the existence of voids [29]. However, when an amount of soil is compressed and stress is applied, the void ratio is expected to decrease as the soil is compressed [53]. Water absorption is an indicator of the resistance of CEB samples to water intrusion. Figure 6a and b present the results of the water absorption of the CEB samples containing varying amounts of waste tire rubber residue with and without the addition of cement.

Fig. 6 **a** Effect of waste tire residue on the water absorption of CEB samples. **b** Effect of blended cement-waste tire residue on the water absorption of the CEB samples

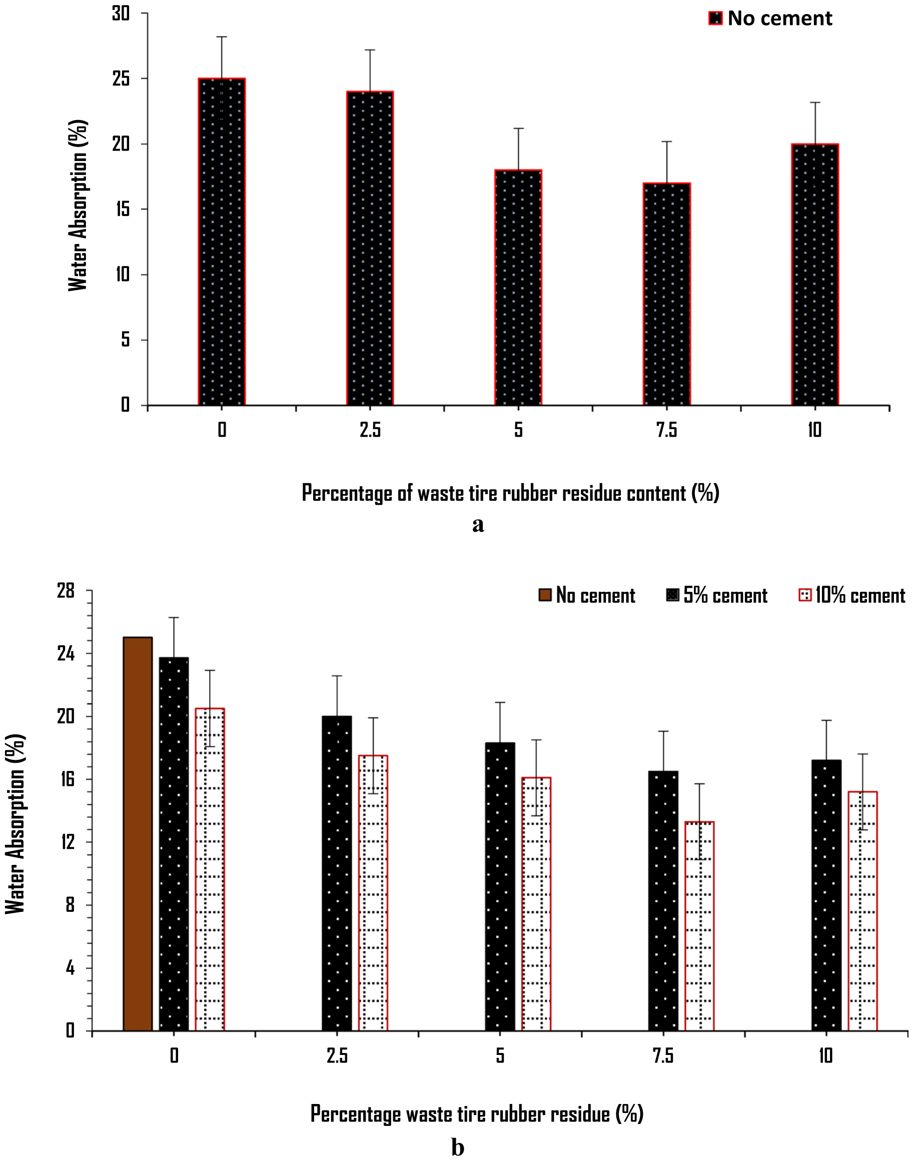


Figure 6a shows the outcomes of the water absorption test on the CEBs stabilized with only waste tire rubber residue relative to the control. The figure shows that the average water absorption value for the control (unstabilized CEBs) was 25%. This recorded value for a reference is high, which could be a result of fractures on the CEB surfaces causing accumulation of water in the earth brick. When the CEBs were stabilized with 2.5, 5, 7.5 and 10% of waste tire rubber residue without cement, the average water absorption was 24%, 18%, 17% and 20%, respectively. The recorded results are lower than those obtained for the control samples, indicating that the waste tire rubber residue, due to its very low absorption property, causes the CEBs to absorb less water. However, the observed water absorption results are still relatively high compared to the minimum requirement recommended by [48]. The water intake capacity of CEBs tends to decrease with increasing amounts of pulverized waste tire rubber residue.

Figure 6b shows the water absorption results for the CEBs stabilized with blended cement-waste tire rubber residue relative to those of the control. The figure shows that the water absorption of the stabilized CEBs (for both the control and those containing waste tire rubber residue) tends to decrease with increasing amounts of blended cement-pulverized waste tire rubber residue. This could be a result of a reduction in the pores and fractures in the CEBs caused by the presence of the cementing agent and sufficient curing. The recorded average water absorption for the stabilized reference CEBs (0% waste tire) at 5% and 10% cement content was 23.7% and 20.5%, respectively, relative to 25% (unstabilized—no cement and waste tire). The outcomes decreased by 5.2% and 18%, respectively. Similar decreasing trends in water absorption were observed for CEBs stabilized with blended cement-waste tire rubber residue at cement contents of 5% and 10%. The results show average water absorption values of 20% and 17.5% (2.5%), 18.3% and 16.1% (5%), 16.6% and 13.3% (7.5%) and 17.2% and 15.2% (10%) at 5% and 10% cement content, respectively. The average percentage decrease is approximately 10% at 5% cement content and 21% at 10% cement content. The water absorption test on the CEBs showed that stabilizing the soil composite mixes with blended cement-pulverized waste tire rubber residues influences the water intake tendency of the CEBs by reducing their capacity to take in moisture, even when the earth bricks are deployed in a damp environment. This approach could ensure the reliability of buildings made with CEBs stabilized with blended cement-waste tire rubber residues. Moreover, the water absorption values for the stabilized earth bricks surpassed the minimum requirement recommended by [48]. It is also possible that the incorporation of cement to stabilize the CEB helps to achieve good compaction of the CEB, hence decreasing the water absorption tendency of the earth bricks. The results from this study are similar to those of previous works by [24, 29, 54–57].

3.5 Modeling the effect of cement content and waste tire rubber residue on compressive strength and water absorption of CEB

A mathematical relationship was developed using response surface analysis to establish the interaction effect of the cement content and waste tire rubber materials in the soil mixes on the compressive strength and water absorption tendency of the CEB. Analysis of variance (ANOVA) was also carried out to determine whether the effect of these parameters was statistically significant at a 95% confidence interval (CI), that is, a p value < 0.05. The ANOVA results, as presented in Table 5 for the compressive strength of the CEB, showed that both the quadratic (X_1^2, X_2^2) and interaction terms ($X_1 X_2$)

Table 5 ANOVA for compressive strength of CEB mixes

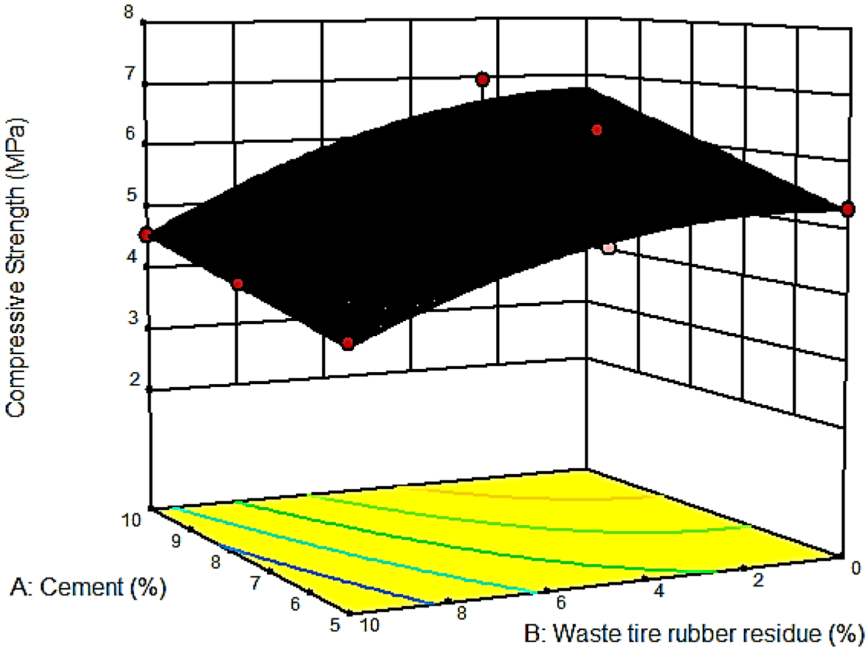
Source	Sum of squares	DoF	Mean square	F value	p value Prob > F	
Model	9.88	5	1.98	33.88	< 0.0001	Significant
Cement—X_1	2.26	1	2.26	38.67	0.0004	
Waste tire rubber residue—X_2	5.66	1	5.66	97.05	< 0.0001	
$X_1 X_2$	0.12	1	0.12	2.07	0.1939	
X_1^2	2.038E−006	1	2.038E−006	3.493E−005	0.9954	
X_2^2	0.67	1	0.67	11.43	0.0118	
Residual	0.41	7	0.058			
Lack of Fit	0.41	5	0.082			
Pure Error	0.000	2	0.000			
Cor Total	10.29	12				

DoF: degree of freedom

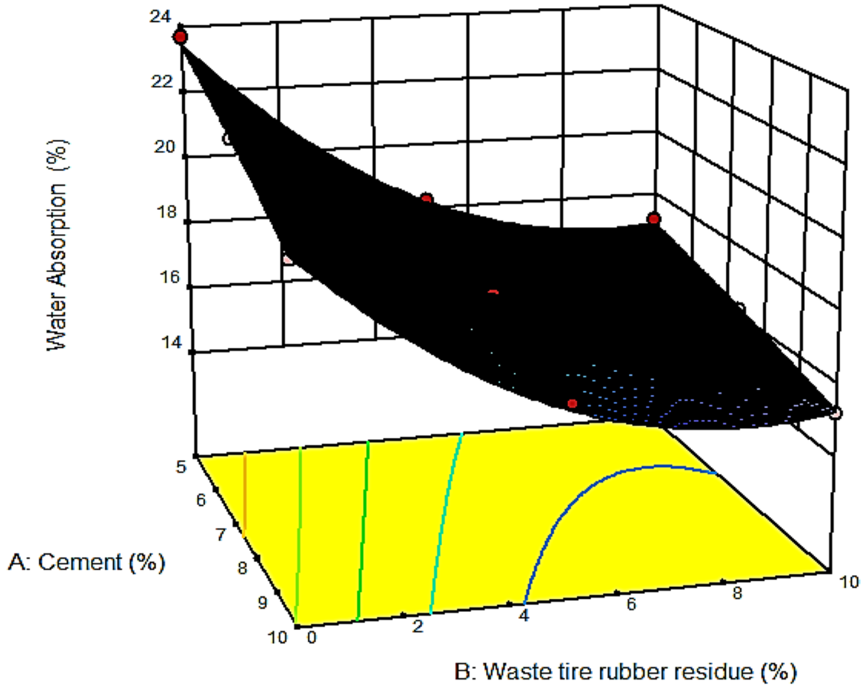
are statically insignificant. However, the linear terms for cement (X_1) and waste tire rubber residue (X_2) were significant in terms of the compressive strength development of the CEB.

Figure 7a shows the response surface plot for the compressive strength of the stabilized CEBs with a blend of cement and waste tire rubber residue. The figure reveals that the cement content plays a significant role in the improved compressive strength development of the CEBs, coupled with the effect of the waste tire rubber residue at low dosage additions in the range of 0–6% mass of the cement. The interaction between the blended cement and waste tire rubber residue

Fig. 7 **a** Response surface plot of the compressive strength of the CEB. **b** Response surface plot of water absorption by CEB



a



b

in the CEBs indicates that increasing the cement content impacts the compressive strength, while increasing the tire rubber residue material causes a gradual decrease in the compressive strength.

The model for the compressive strength is presented in Eq. (3). The parameters for the model are shown in Table 6. The model has an R-square (R^2) value of 0.96, and the predicted R-square (Pred. R^2), with a value of 0.89, is in moderate agreement with the adjusted R-squared (Adj R^2) value of 0.93.

$$\textit{Compressive strength}, Y_{CS} = 3.79 + 0.30X_1 + 0.11X_2 - 0.01X_1X_2 + 0.0001X_1^2 - 0.02X_2^2 \tag{3}$$

In addition, a model relationship was developed to establish the effect of the interaction between the cement content and waste tire rubber materials in the soil mixture on the water absorption rate of the CEB. The ANOVA results as presented in Table 7 at the 95% CI showed that both the interaction term ($X_1 X_2$) and the quadratic effect from cement ($X_1{}^2$) were statistically insignificant. However, the linear terms for cement (X_1) and waste tire rubber residue (X_2) and the quadratic term for waste tire rubber residue ($X_2{}^2$) were significant for the water absorption resistance of the CEB.

Figure 7b also shows that the interaction effect of the blend of cement and waste tire rubber residue materials in the soil composite mixes causes a decreasing trend in the water absorption tendency in the resultant CEB samples.

The model for water absorption is presented in Eq. (4). The outcomes of the parameters for the model are shown in Table 8. The model has an R^2 value of 0.99, which is close to unity, and a Pred R^2 value of 0.98, which is in close conformity with the value of the "Adj R^2" of 0.99.

$$\textit{Water absorption}, Y_{wa} = 25.67 - 0.38X_1 - 1.54X_2 + 0.02X_1X_2 - 0.01X_1^2 + 0.08X_2^2 \tag{4}$$

Using response surface analysis, an optimum mixture was developed to establish the optimum composition for the CEB mixes that achieved a target compressive strength of 5 MPa and a water absorption tendency of no more than 18%. The durability of the CEB was also assessed by limiting the cement content to less than 10% and maximizing

Table 6 Outcomes of the model parameters

Std. Dev	0.24	R^2	0.96
Mean	5.45	Adj R^2	0.93
C.V. %	4.43	Pred R^2	0.89
		Adeq Precision	18.538

Table 7 ANOVA for water absorption of CEB mixes

Source	Sum of squares	DoF	Mean square	F Value	*p* value Prob > F	
Model	75.99	5	15.20	422.79	< 0.0001	significant
Cement—X_1	9.28	1	9.28	258.24	< 0.0001	
Waste tire rubber residue—X_2	52.61	1	52.61	1463.58	< 0.0001	
$X_1 X_2$	0.27	1	0.27	7.53	0.0288	
$X_1{}^2$	0.018	1	0.018	0.51	0.4975	
$X_2{}^2$	11.23	1	11.23	312.29	< 0.0001	
Residual	0.25	7	0.036			
Lack of Fit	0.25	4	0.063			
Pure Error	0.000	3	0.000			
Cor Total	76.24	12				

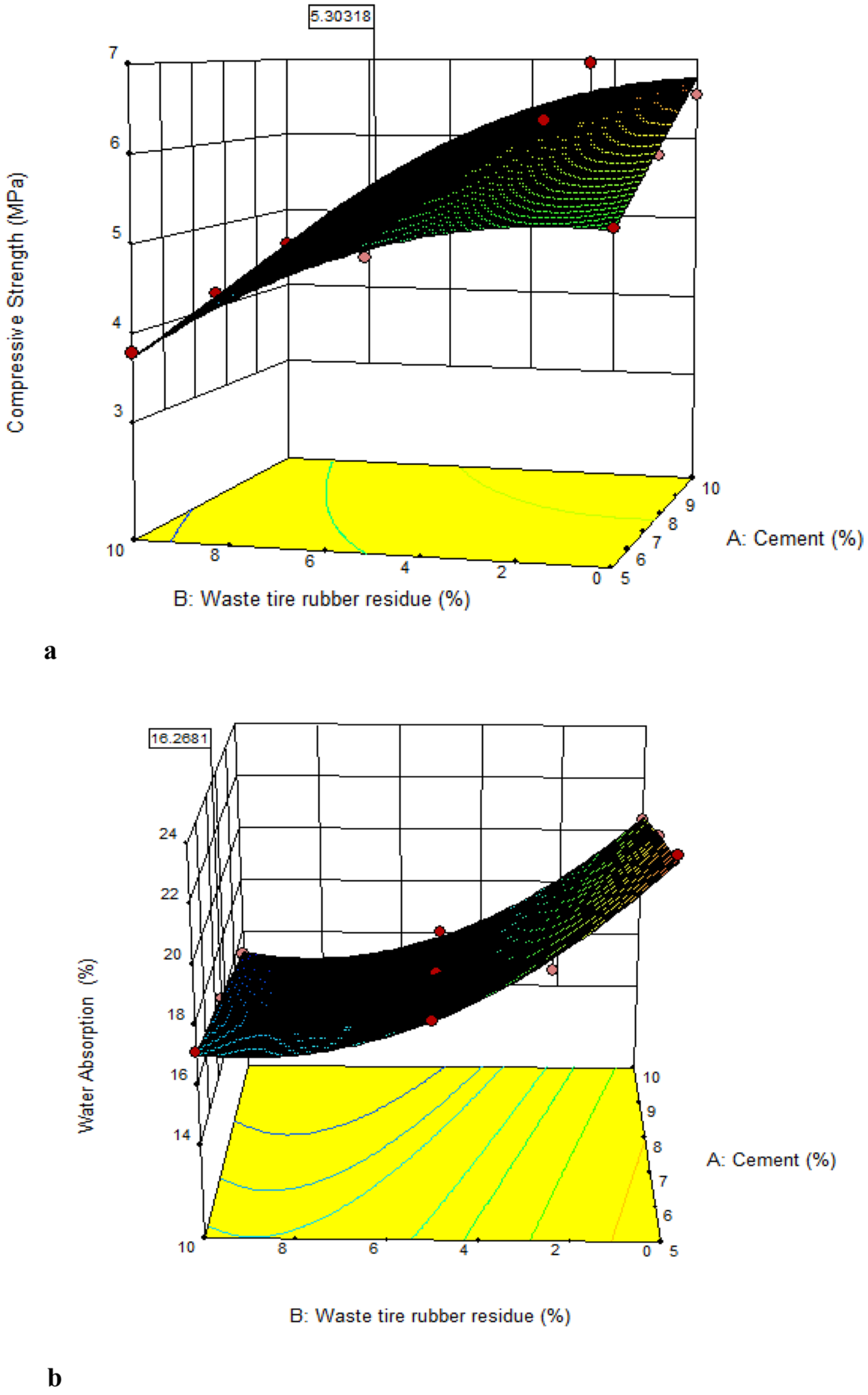
DoF: degree of freedom

Table 8 Outcomes of the model parameters

Std. Dev	0.19	R^2	0.99
Mean	18.32	Adj R^2	0.99
C.V. %	1.04	Pred R^2	0.98
		Adeq Precision	63.548

the quantity of waste tire rubber residue in the CEB mixes. Figure 8a and 8b depict the outcomes of the numerical optimization analysis carried out at 95% confidence prediction and a desirability value of 0.9. The results showed that a CEB composite mixture of 100% soil, 7.5% cement, 6% waste tire rubber residue, and a cement-to-water ratio of 11.7% cured for 28 days yielded a compressive strength value of 5.30 MPa and a water absorption value of 16.3%. These values are well within the minimum requirement recommended by the African Organization for Standardization [47] standard for compressed earth brick used for structural and masonry applications.

Fig. 8 **a** Numerical optimization of the compressive strength for the CEB composite. **b** Numerical optimization of water absorption for the CEB composite



4 Conclusion

This investigation was conducted to study the suitability of using scrap rubber tires crushed into rubber residue form and blended with cement in soil mixes for the possible production of a sustainable medium-strength CEB that can be beneficially deployed for structural and masonry applications. This study concentrated on examining the material properties of the constituents, namely, soil, cement and waste tire rubber residue, and investigating the density, compressive strength and water absorption of the produced compressed earth bricks. Based on the experimental results, the following conclusions can be drawn:

i. Based on the USCS classification, the locally sourced soil used in this study is classified as CL—silty clay of low plasticity, and other observed index properties suggest that the soil is suitable for making CEB. Meanwhile, the low specific gravity and water absorption values of the waste tire rubber residue indicated that the material is lighter and did not absorb water.
ii. Compared with that of the control, the hardened density of the compressed earth bricks was slightly higher by about 4% when only waste tire rubber residue was incorporated into the soil mixture. However, the density slightly improved by about 1.2% with the further addition of cement to the mixes at both percentages considered. This implies that the addition of cement-tire crumb materials to the soil mixture make the bricks denser through improved bonding and compacting efforts.
iii. The results showed a gradual decrease in the compressive strength of the CEB with increasing waste tire rubber residue content in the soil mixes. However, a slight improvement in the compressive strength was observed at a low level of 2.5% incorporation compared to that of the control. The findings indicated that the utilization of waste tire rubber residue is beneficial for making CEB for nonload purposes. The loading requirements should be limited to 1 MPa or less. In a CEB of 2 MPa, the optimum amount of waste tire rubber crumbs should be limited to 2.5% of the soil mass or less in earth bricks.
iv. Moreover, a gradual improvement in the compressive strength was recorded with the addition of cement into the soil mixture. The findings showed that the addition of blended cement-waste tire rubber residue material to the soil mixture significantly improved the CEB strength. The compressive strength increased by approximately 141.5% at 5% cement content and a further 21% increase at 10% cement content compared to the control and CEB with only waste tire rubber residue without cement content. This can be linked to formation of CSH gel in the CEB pores, resulting in improved adhesion and bonding. However, a gradual decrease in the recorded compressive strength was still observed as the waste tire rubber residue content increased in the mixes.
v. Nonetheless, it should be stated that the compressive strength values recorded for all the CEBs stabilized with blended cement-waste tire rubber residue meet the recommended minimum compressive strength requirements of 1 MPa and 3 MPa suggested by the Turkish standard and African Organization for Standardization, respectively.
vi. The water absorption rate of the CEBs tended to decrease with increasing amounts of waste tire rubber residue due to its hydrophobic property. Similarly, for CEBs stabilized with blended cement-waste tire rubber residue, the water absorption rate exhibited the same declining trend. This indicates that durable CEBs with enhanced water resistance can be produced with blended cement-waste tire rubber residue.
vii. The models developed indicated that both waste tire rubber residue material and cement content had significant influences on the response variables. However, the linear interaction effects are more substantial in the models. The optimization outcomes showed that a CEB composite mixture of 100% soil, 7.5% cement, 6% waste tire rubber residue, and a cement-to-water ratio of 11.7% cured for 28 days would yield a target compressive strength value of approximately 5.30 MPa and a water absorption value range of 16.3%.

These findings demonstrated the possibility of making sustainable medium-strength CEBs containing waste tire rubber residue and cement with good water intake resistance that can be used for structural work. The reuse of discarded tires in CEB offered a sustainable, innovative means of recycling waste tires. This approach will be beneficial to the built environment of many developing countries and provide a cheap innovative means of eliminating the menace of indiscriminate open dumping of waste tires into water bodies and the resulting nuisance it causes the environment due to its nonbiodegradable nature.

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Data availability The authors declare that all data supporting the findings of this study are available within the paper. However, additional request for supplementary data generated during the current study will be made available by the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

1. Wilson DC, Webster M. Building capacity for community waste management in low-and-middle income countries. Waste Manage Res. 2018;36:1–2.
2. Lagerkvist A, Dahlén L. Solid waste generation and characterization. In: Meyers RA, editor. Encyclopedia of sustainability science and technology. New York: Springer; 2012. https://doi.org/10.1007/978-1-4419-0851-3_110.
3. Letshwenyo MW, Kgetseyamore D. Generation and composition of municipal solid waste: case study, extension 7, Palapye, Botswana. SN Appl Sci. 2020;2:1665. https://doi.org/10.1007/s42452-020-03496-2.
4. Kaza S, Yao LC, Bhada-Tata P, Van Woerden F, What a Waste 2.0: a global snapshot of solid waste management to 2050, 2018. https://doi.org/10.1596/978-1-4648-1329-0.
5. United Nations Environmental Programme (UNEP) 2024 Global Waste Management Outlook 2024. https://www.unep.org/resources/global-waste-management-outlook-2024. Accessed 08 July 2024.
6. Wilson DC, Rodic L, Modak P, Soos R, Carpintero A, Velis C, Iyer M, Simonett O. Global Waste Management Outlook. Report. UNEP DTIE. 2015, ISBN: 978-92-807-3479-9.
7. Mbama CA, Otegbulu A, Beverland I, Beattie TK. Solid waste recycling within higher education in developing countries: a case study of the University of Lagos. J Mater Cycles Waste Manag. 2023;25:886–98. https://doi.org/10.1007/s10163-022-01569-5.
8. Mohajerani A, Burnett L, Smith JV, Markovski S, Rodwell G, Rahman MT, Kurmus H, Mirzababaei M, Arulrajah A, Horpibulsuk S, Maghool F. Recycling waste rubber tyres in construction materials and associated environmental considerations: a review. Resour Conserv Recycl. 2020;155: 104679. https://doi.org/10.1016/j.resconrec.2020.104679.
9. Torretta V, Rada EC, Ragazzi M, Trulli E, Istrate IA, Cioca LI. Treatment and disposal of tyres: two EU approaches. A review. Waste Manag. 2015;45:152–60.
10. Blaifi H, Guendouz M, Belhadj A, Boukhelkhal D, Hadjadj M. Sustainable use of recycled plastic and ceramic industrial wastes in eco-friendly construction materials. Environ Eng Manag J. 2023;22(8):1471–86. https://doi.org/10.30638/eemj.2023.124.
11. Guendouz M, Boukhelkhal D, Bourdot A. Recycling of floor tile waste as fine aggregate in flowable sand concrete. In: Chiba Y, Tlemçani A, Smaili A, editors. Advances in green energies and materials technology. Springer Proceedings in Energy. Singapore: Springer; 2021. https://doi.org/10.1007/978-981-16-0378-5_30.
12. Boukhelkhal D, Guendouz M, Bourdot A, Cheriet H, Messaoudi K. Elaboration of bio-based building materials made from recycled olive core. MRS Energy Sustain. 2021;8:98–109. https://doi.org/10.1557/s43581-021-00006-8.
13. Guendouz M, Boukhelkhal D, Mechantel A, Boukerma T. Valorization of coffee waste as bio-aggregates in crushed sand concrete production. Environ Eng Manag J. 2023;22(1):147–56. https://doi.org/10.30638/eemj.2023.013.
14. Benimam S, Bentchikou M, Debieb F, Kenai S, Guendouz M. Physical and mechanical properties of cement mortar with LLDPE powder and PET fiber wastes. Adv Concrete Constr. 2021;12(6):461–7. https://doi.org/10.12989/acc.2021.12.6.461.
15. Hadjadj M, Guendouz M, Boukhelkhal D. The effect of using seashells as cementitious bio-material and granite industrial waste as fine aggregate on mechanical and durability properties of green flowable sand concrete. J Build Eng. 2024;87: 108968. https://doi.org/10.1016/j.jobe.2024.108968.
16. Vera S. La contaminación atmosférica por las actividades de la industria de la construcción en Colombia. *Repositorio Digital Institucional*. Universidad César Vallejo. 2019. https://www.researchgate.net/profile/Javier-Vera-Solano/publication/336749294_Air_pollution_from_construction_industry_activities_in_Colombia/links/5db0b5fc299bf111d4c022e9/Air-pollution-from. Accessed 15 May 2022.
17. Aranda-Jiménez Y, Zuñiga-Leal C, Moreno-Chimely L, Robles-Aranda ME. Compressed earth blocks (CEB) compression tested under two earth standards. Cogent Eng. 2023;10: 2163116.

18. Herrera Villa J. Modelamiento numérico del comportamiento sísmico de viviendas de mampostería con bloques de tierra comprimida. Tesis de magíster. Pontificia Universidad Católica del Perú. Recuperado de 2018. http://tesis.pucp.edu.pe/repositorio/handle/20.500.12404/12059
19. Waziri BS, Lawan ZA, Mala M, Shehu Waziri B, Alhaji Lawan Z, Mala A. Properties of compressed stabilized earth blocks (CSEB) for low-cost housing construction: a preliminary investigation. Int J Sustain Constr Eng Technol. 2013;4:2180–3242.
20. Gómez-Patrocinio FJ, García-Soriano L, Vegas F, Mileto C. Técnicas y características de los muros mixtos de tierra y madera. El caso de España. Inf Constr. 2021;73(561):e372–e372. https://doi.org/10.3989/ic.73876.
21. Akinwumi II, Awoyera PO, Bello OO. Indigenous earth building construction technology in Ota, Nigeria. Indian J Tradit Knowl. 2015;14:206–12.
22. Bouchefra I, Bichri FZ, Chehouani H, Benhamou B. Mechanical and thermophysical properties of compressed earth brick reinforced by raw and treated doum fibers. Constr Build Mater. 2022;318: 126031.
23. Pelé-Peltier A, Charef R, Morel JC. Factors affecting the use of earth material in mainstream construction: a critical review. Build Res Inf. 2022. https://doi.org/10.1080/09613218.2022.
24. Abdullah A, Nagapan S, Antonyova A, Rasiah K, Yunus R, Sohu S, Comparison of strength between laterite soil and clay compressed stabilized earth bricks (CSEBs), In: Proceedings of the MATEC Web of Conferences. 2017; 103, 01028, pp. 1–8.
25. Busari AA, Akinwumi II, Awoyera PO, Olofinnade OM, Tenebe JC, Nwanchukwu TI. Stabilization effect of aluminum dross on tropical lateritic soil. Int J Eng Res Africa. 2018;39:86–96.
26. Muhit IB. Evaluation of stabilized soil blocks with the inclusion of 'Plastic Fiber' as sustainable building material: a complete review. Int Conf Mech Ind Mater Eng. 2013; 1–5.
27. Akinwumi II, Domo-Spiff AH, Salami A. Marine plastic pollution and affordable housing challenge: shredded waste plastic stabilized soil for producing compressed earth bricks. Case Stud Constr Mater. 2019;11: e00241.
28. Akinwumi II, Booth CA. Experimental insights of using waste marble fines to modify the geotechnical properties of a lateritic soil. J Environ Eng Landsc Manage. 2015;23:121–8.
29. Villamizar MCN, Araque VS, Reyes CAR, Silva RS. Effect of the addition of coal-ash and cassava peels on the engineering properties of compressed earth blocks. Constr Build Mater. 2012;36:276–86.
30. Akinwumi II, Ajayi OO, Joshua O, Sani R, Olofinnade OM, Awoyera PO, Ogundairo TO, Ogunwole DA, Afolayan OD. Housing crisis: waste glass-stabilized clay for use as fired clay bricks. IOP Conf Ser Mater Sci Eng. 2019;640: 012072. https://doi.org/10.1088/1757-899X/640/1/012072.
31. Bekhiti M, Abderrahmane G, Zaitri R. Effects of tyre rubber fiber and glass fiber on physical and mechanical properties of Compressed Earth Block (C.E.B) based on local materials. J King Saud Univ Eng Sci. 2021. https://doi.org/10.1016/j.jksues.2021.01.003.
32. Kumar M. Clay soil stabilization by utilizing secondary lime and rubber tire powder. Mater Today Proc. 2021;37:3471–4. https://doi.org/10.1016/j.matpr.2020.09.383.
33. Al-Subari L, Ekinci A, Aydın E. The utilization of waste rubber tire powder to improve the mechanical properties of cement-clay composites. Constr Build Mater. 2021;300: 124306.
34. Ahmed A, Naggar MHE. Effect of cyclic loading on the compressive strength of soil stabilized with bassanite–tire mixture. J Mater Cycles Waste Manag. 2018;20(1):525–32. https://doi.org/10.1007/s10163-017-0617-1.
35. Kalkan E. Preparation of scrap tire rubber fiber-silica fume mixtures for modification of clayey soils. Appl Clay Sci. 2013;80–81:117–25. https://doi.org/10.1016/j.clay.2013.06.014.
36. Yadav JS, Tiwari SK. A study on the potential utilization of crumb rubber in cement treated soft clay. J Build Eng. 2017;9:177–91. https://doi.org/10.1016/j.jobe.2017.01.001.
37. CCANZ, Cement Stabilization. Cement & Concrete Association of New Zealand. IB89, 2008.
38. Marathe S, Rao BS, Kumar A. Stabilization of lithomargic soil using cement and randomly distributed waste shredded rubber tyre chips. Int J Eng Trends Technol. 2015;23(6):284–8.
39. ASTM D422-63. Standard test method for particle-size analysis of soils. West Conshohocken: ASTM International; 2007.
40. ASTM D854-00. Standard test methods for specific gravity of soil solids by water pycnometer. West Conshohocken: ASTM International; 2000.
41. ASTM D4318-00. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. West Conshohocken: ASTM International; 2000.
42. ASTM D698-07. Standard test methods for laboratory compaction characteristics of soil using standard effort (12 400 ft-lbf/ft^3 (600 kN-m/m^3). West Conshohocken: ASTM International; 2007.
43. NIS 444: Part 1. Composition, specification and conformity criteria for common cements, Abuja, 2003.
44. ASTM C150. Standard specification for Portland Cement, ASTM Standards, 2009.
45. TS 704. Turkish standards on solid brick and vertically perforated bricks (the classification, properties, sampling, testing and marking of solid bricks and vertically perforated bricks): Turkish Standard Institution, 1985.
46. XP P13-901, Compressed earth blocks for walls and partitions: definitions, specifications, test methods, conditions of acceptance, AFNOR. 2001.
47. Touré PM, Sambou V, Faye M, Thiam A, Adj M, Azilinon D. Mechanical and hygrothermal properties of compressed stabilized earth bricks (CSEB). J Build Eng. 2017;13:266–71.
48. WD-ARS 1333 Compressed stabilized earth blocks — Requirements, production and construction, African Organization for Standardization (ARSO), Nairobi, Kenya, 2018.
49. Mazhoud B, Collet F, Pretot S, Lanos C. Mechanical properties of hemp-clay and hemp stabilized clay composites. Constr Build Mater. 2017;155:1126–37. https://doi.org/10.1016/j.conbuildmat.2017.08.121.
50. Islam MS, Elahi TE, Shahriar AR, Mumtaz N. Effectiveness of fly ash and cement for compressed stabilized earth block construction. Constr Build Mater. 2020;255: 119392. https://doi.org/10.1016/j.conbuildmat.2020.119392.
51. Bahar R, Benazzoug M, Kenai S. Performance of compacted cement-stabilized soil. Cem Concr Compos. 2004;26(7):811–20. https://doi.org/10.1016/j.cemconcomp.2004.01.003.

52. Wang FC, Song W. Effects of crumb rubber on compressive strength of cement-treated soil. Arch Civil Eng LXI. 2015;4:59–78. https://doi.org/10.1515/ace-2015-0036.
53. Guettala A, Houari H, Mezghiche B, Chebili R. Durability of lime stabilized earth blocks. Courrier du Savoir. 2002;2:61–6.
54. Raheem AA, Bello OA, Makinde OA. A comparative study of cement and lime stabilized lateritic interlocking blocks. Pac J Sci Technol. 2010;2:27–34.
55. Nagaraj HB, Sravan MV, Arun TG, Jagadish KS. Role of lime with cement in long-term strength of compressed stabilized earth blocks. Int J Sustain Built Environ. 2014;1:54–61.
56. Kamwa RAT, Tome S, Chongouang J, Eguekeng I, Spieß A, Fetzer MNA, Elie K, Janiak C, Etoh M. Stabilization of compressed earth blocks (CEB) by pozzolana based phosphate geopolymer binder: physico-mechanical and microstructural investigations. Cleaner Mater. 2022;4:100062. https://doi.org/10.1016/j.clema.2022.100062.
57. Zainal LA, Burhanudin MK. Physical and mechanical properties of compressed earth brick (CEB) with palm oil fuel ash (POFA) as cement replacement. Recent Trends Civil Eng Built Environ. 2024;4(3):244–50.