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Scientific Paper

Sustainable stabilized compressed earth blocks from construction and demolition waste

Blocos de terra comprimida estabilizados sustentáveis de resíduos de construção e demolição

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ABSTRACT

While crucial to global socioeconomic progress, the construction industry is a significant waste generator, presenting substantial environmental challenges. To promote the recycling of construction and demolition waste (CDW), this study was conducted on the manufacturing of soilless and low-stabilizer stabilized compressed earth blocks (SCEBs), with the aim of producing blocks with high mechanical strength. The study included the characterization of CDW and the determination of its optimal compression parameters for manufacturing SCEBs, using a minimal amount of blast-furnace slag cement as a binder. The resulting SCEBs, containing 4% cement, were then evaluated for their mechanical properties, including compressive strength and diametrical tensile strength, mass loss, pH, carbonation test, and thermogravimetric analysis. The results indicate that the manufacturing of sustainable blocks using 100% CDW requires the addition of a stabilizer. Considering the scarcity of research on the development of high-performance bricks with high mechanical strength made entirely with residue and a low binder index, the SCEB-4 sample demonstrates that it is possible to manufacture bricks with total replacement of raw earth by CDW and only 4% cement that replace types BTC 20, BTC 40 and, even BTC 60, surpassing their nominal mechanical strength. SCEBs with a reduced blast-furnace slag cement content hold promise for CDW recycling, mitigating its improper disposal, conserving natural resources, and contributing to the reduction of atmospheric carbon dioxide by reusing carbonated waste.

Keywords: unfired brick; stabilized compressed earth block; blast-furnace slag cement; recycled aggregates; sustainable block.

RESUMO

Embora crucial para o progresso socioeconômico global, a indústria da construção é geradora significativa de resíduos, apresentando desafios ambientais substanciais. Para promover a reciclagem de resíduos de construção e demolição (RCD), foi realizado um estudo sobre a fabricação de blocos de terra comprimida estabilizada (BTCE) sem solo e com baixo teor de estabilizante, visando à obtenção de um bloco com alta resistência mecânica. A pesquisa abrangeu a caracterização do RCD e a determinação dos parâmetros ideais de compressão para a fabricação, utilizando uma quantidade mínima de cimento de escória de alto-forno como aglutinante. O BTCE resultante, contendo 4% de cimento, foi então avaliado quanto às propriedades mecânicas, incluindo resistência à compressão e tração diametral, perda de massa, pH, carbonatação e análise termogravimétrica. Os resultados indicaram que a fabricação de blocos sustentáveis com 100% de RCD requer a adição de um estabilizante. Considerando a escassez de pesquisas no desenvolvimento de tijolos de alto desempenho em resistência mecânica feitos inteiramente com resíduo e baixo índice de ligante, a amostra do BTCE-4 demonstra que é possível fabricar tijolos com a substituição total da terra bruta por RCD e com apenas 4% de cimento que substitui os tipos BTC 20, BTC 40, incluindo o BTC 60, superando sua resistência mecânica nominal. Os BTCEs com teor reduzido de cimento de escória de alto-forno são promissores para a reciclagem de RCD, mitigando o seu descarte inadequado, conservando os recursos naturais e contribuindo para a redução do dióxido de carbono atmosférico ao reutilizar resíduos carbonatados.

Palavras-chave: tijolo cru; tijolo de terra comprimida estabilizado; cimento de escória de alto-forno; agregados reciclados; bloco sustentável.

INTRODUCTION

Although the construction industry is a sector of great importance for the economic and social development of the world, it is also a major generator of waste, with a significant environmental impact. The generation and management of construction and demolition waste (CDW) are influenced by several factors, such as urbanization, standards and regulatory measures for waste, and gross domestic product (GDP) (Aslam; Huang; Cui, 2020). According to the *Service des données et études statistiques* (SDES, 2024), more than 212 million tons (Mt)

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of waste from civil construction was generated in 2020, and the extraction of non-metallic minerals, used mainly in civil construction, in French territory reached 394 Mt in 2021, or 5.8 tons per inhabitant.

Several researchers have made significant efforts toward the advancement and continued development of CDW management (Aslam; Huang; Cui, 2020). Much of the current research has focused on the characterization of CDW (Hoong *et al.*, 2020; Zhao *et al.*, 2023) and its recycling for various applications, such as compaction in road paving (Garzón *et al.*, 2022), as well as the manufacturing of mortars, bricks, and cementitious materials (Bogas; Silva; Gomes, 2019; Ahmad *et al.*, 2023; Zhao *et al.*, 2023; Morselli *et al.*, 2024). In addition to contributing to the sustainability in civil construction, the use of waste in brick manufacturing is an effective method for disposing of abundant waste which contributes to the depletion of natural resources. Moreover, incorporating such waste can enhance the properties of the manufactured bricks (Al-Fakih *et al.*, 2019).

Raw earth blocks can generally be divided into two types: unstabilized compressed earth blocks (CEBs), which are produced by compressing clay soil in the wet state with immediate demolding, and stabilized compressed earth blocks (SCEBs), with mixing a hydraulic binder with clay soil to enhance the performance of the blocks (NF EN, 2001). CEBs are adobe bricks compacted under high pressure, known for their low thermal conductivity, which imparts greater energy efficiency to buildings (Kidari; Tilioua, 2024).

Although CEBs have certain limitations such as water permeability and resistance to cracking, ongoing research efforts are focused on their improvement with the use of additives (Labiad; Meddah; Beddar, 2023) such as wood biomass ash (Boussaa; Kheloui; Chelouah, 2023), cassava wastewater biopolymer (Souza *et al.*, 2021), and sisal fiber (Labiad; Meddah; Beddar, 2023; Latha; Murugesan, 2024), and the incorporation of waste to replace the land, such as recycled aggregates (Bogas; Silva; Gomes, 2019; Malkanthi; Wickramasinghe; Perera, 2021; Morselli *et al.*, 2024). SCEBs made with a mixture of construction waste contribute to the management of environmental challenges and offer a promising solution to the problem of the scarcity of natural resources (Malkanthi; Wickramasinghe; Perera, 2021).

There is still limited research focused on the manufacturing of bricks with a total replacement of raw earth by CDW and lower levels of hydraulic binders, such as cement (Ahmad *et al.*, 2023). The widespread use of mineral binders, such as lime and cement, for stabilizing building materials raises concerns about the responsible use of environmental resources. This practice, often employed to enhance the water resistance, mechanical performance, and handling of CEBs, prompts questions about the genuine necessity of such stabilization methods (Ouedraogo *et al.*, 2020). According to Ouedraogo *et al.* (2020), the use of up to 4% cement for stabilizing CEBs is considered environmentally sustainable, as it produces water-resistant bricks with compressive strength varying between 4 and 8 MPa. According to Bogas, Silva and Gomes (2019), a minimum of 4% cement is sufficient to produce water-resistant CEBs with partial incorporation of recycled aggregates.

Considering that there is a lack of research regarding the production of CEBs with higher mechanical resistance, incorporating waste instead of raw earth with reduced levels of hydraulic binders to achieve greater strength, this study aimed to fabricate blocks with greater mechanical resistance. To enable the total substitution of natural soil with CDW in the manufacturing of CEBs, this study included the physical and chemical characterizations of waste and the fabrication of its compression parameters , using a minimal amount of blast-furnace slag cement as a binder. The resulting SCEBs, made with 4% cement, were evaluated for their physicochemical parameters such as mechanical behavior, compressive strength, diametral tensile strength, loss of mass, pH, carbonation test, and thermogravimetric (TG) analyses.

METHOD

Material

CDW, collected from a recycling platform in La Rochelle, France, was used for this study. A homogeneous batch of CDW was utilized in this study to minimize compositional variability and ensure the consistency of results for the manufactured blocks. The CDW is composed mainly of concrete grains, ceramic materials, bituminous materials, natural aggregates, and, in smaller quantities, glass, wood, plastics, metals, and others (Hoong *et al.*, 2020). The cement used is classified as CEM III/A 42.5 N, supplied by EQIOM company and manufactured in La Rochelle, France. It is a blast-furnace slag cement, with a dry density (ρ) of 2.94 g cm^{-3}. Due to its lower clinker content (38 wt%) compared to Portland cement, it offers a more favorable environmental impact (Morselli *et al.*, 2024).

Preparation and characterization of CDW

The material was dried at 105°C for 24 h and then sieved to obtain a particle size range of 0–6.3 mm (0/6.3 mm). Particle size analysis was performed in accordance with European standard NF EN 933-1 (NF EN, 2016) using dry sieving for granular fractions larger than 500 µm, without washing. The analysis was performed in triplicate, and particles smaller than < 500 µm were analyzed using laser diffraction in a CILAS 1090 device particle size analyzer.

Analyses of bulk density and surface dry specific density were performed in quadruplicate, in accordance with European standards (NF EN, 1998; 2014; 2016). Methylene blue adsorption value (MBV), also called stain test, was determined to evaluate the quantity and activity of the clay fraction in the soil based on the amount of methylene blue adsorbed. The analysis was conducted in accordance with European standard NF EN 933-9 (NF EN, 2022).

The calcimetry test determines the calcium carbonate ($CaCO_3$) content by the stoichiometry of the materials by indirectly measuring the volume of carbon dioxide (CO_2) released by the decomposition of a known amount of $CaCO_3$ while reacting with hydrochloric acid (HCl) in a device known as a calcimeter. When adding a dilute solution of HCl to a material containing $CaCO_3$, there occurs a reaction that releases H_2O, $CaCl_2$, and CO_2. The volume of CO_2 released can be measured, and by assuming its similarity to a perfect gas, the amount of $CaCO_3$ can be calculated using the ideal gas law. For each of the repetitions in triplicate, 0.80 g of material was used. The pH measurement was carried out by a 1:5 weight ratio of material to liquid. The mixture was stirred for 3 min at 120 rpm before measurement with a Mettler Toledo S210 pH meter.

TG and derived thermogravimetry (DTG) analysis was performed for the identification of the mass loss of the materials as a function of increasing temperature (Figure 1). The TG analysis was conducted using a Nabertherm furnace model B400/B410 with a temperature range of 30–950°C and a heating rate of 10°C/min, with approximately 30 g of recycled sand properly dried in a ventilated oven at 105°C used for the analysis.

The loss to fire up to 950°C of the CDW was 8.94%, according to the TG/DTG graph (Figure 1). No free water loss from the material was demonstrated up to 105°C because the CDW was already in a dry condition. Up to 400°C, the loss of 1% of the mass of the CDW was attributed to the dehydration of the cementitious matrix present in the concrete grains, mainly hydrated calcium silicates (C–S–H). From 400 to 500°C, the loss of 0.55% corresponded to the decomposition of calcium hydroxide or portlandite (CH) in free lime ($Ca(OH)_2$). From 500 to 800°C, the mass loss of 2.91% corresponded to the decarbonation of calcite ($CaCO_3 \rightarrow CaO+CO_2$) (Oliveira *et al.*, 2023).

The modified Proctor test was carried out to determine the dry bulk density (ρ_d) and the optimal water content (W_{NPO}) in accordance with European standard NF EN 13286-2 (NF EN, 2010). The material (0/6.3 mm) was dried at 105°C for 24 h and air-cooled until room temperature. This test consists of compacting the materials with different percentages of water contents (from 6 to 14% every 2%) in a cylindrical metal mold of 2,297 cm^3. The compaction energy corresponds to the checker used (4.5 kg) and the imposed number of checker strokes per layer (56 strokes). From the modified Proctor test (Figure 2), a dry density of 1.91 g cm^{-3} was obtained for the optimal moisture content of 12%.

Determination of water content and cement quantity

The modified Proctor test demonstrates the optimal water content and cement quantity; however, its compaction energy is lower than that of the compressed blocks. To ensure consistency with real manufacturing conditions, mechanical performance was evaluated through compaction tests conducted with a Zwick/Roell Z100 press machine at a pressure of 43 MPa. The tests were performed with varying water contents (8, 9, 10, and 11%), with a dry density of approximately 2.00 g cm^{-3}.

For each sample, the materials were weighed using a 0.1 g precision balance, then placed in molds in three equal layers, and compacted with the aid of a demolding piston, which compacts the material ten times from a fixed height before mechanical compression. Cylindrical samples measuring 50 mm in diameter and 50 mm in height, and with 98.2 cm^3 of total volume, were made by axial compressions using a Zwick/Roell Z100 press at a pressure of 43 MPa for complete closure of the molds and were extruded by axial compressions, following the principles outlined in European standard NF EN 13286-53 (NF EN, 2005b). The optimal moisture content was determined to be 9% as it produced samples with compressive strength exceeding 1 MPa (Figure 3a). Linear regression analyses were conducted using Microsoft Excel®.

To determine the amount of binder, the water content (9%) and compactness (0.84) were maintained, similar to those of the sample. A volumetric replacement of CDW (0/6.3 mm) with varying amounts of cement was carried out. The cement was added and mixed immediately before the compaction at the machine. The samples were weighed and measured after demolding. The quantity of 0–14% cement replacing CDW by weight was evaluated for compressive strength analysis at zero time, immediately after demolding (Figure 3b).

Increasing the binder content, such as cement in CEBs, increases compressive strength, corroborating findings from Bouchefra *et al.* (2021). After analyzing the behavior of the specimens (Figure 3a), the bricks were produced with 4 wt% cement, using the same manufacturing parameters as before (cylindrical samples measuring 50 mm in diameter and 50 mm in height, with a total

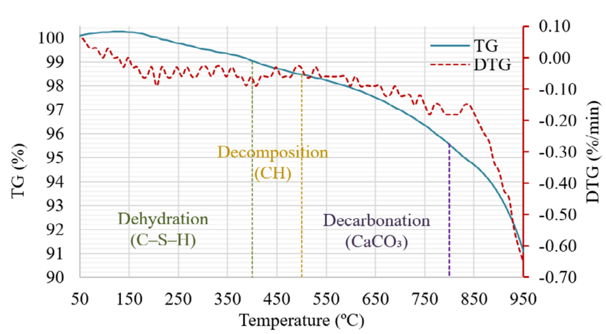

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Figure 1 – Graphical illustration of thermogravimetric (TG) and derived thermogravimetric (DTG) analysis of CDW.

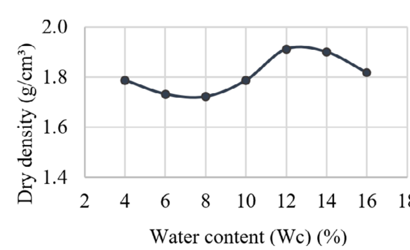

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Figure 2 – The modified Proctor test of the CDW.

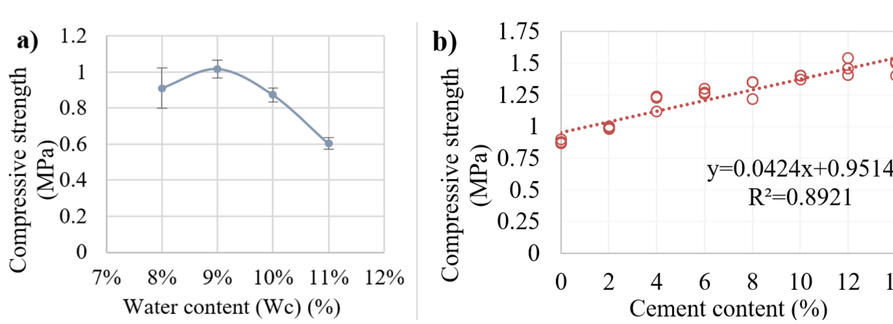

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Figure 3 – (a) Compression test results for samples prepared with varying water contents, and (b) compressive strength of samples with varying cement content (wt%).

volume of 98.2 cm^3, under a pressure of 43 MPa). The choice was made based on the compressive strength results with the most significant increase between 2 and 4% of cement replacement by CDW (Figure 3a). In addition, this value remains below 5% (± 2) of Portland cement content used in commercial stabilized raw earth bricks (Cycle Terre, 2021).

Two block treatments were prepared: one using only CDW, as sample "CEB-0," and another with 4% cement, as sample "SCEB-4." The samples were wrapped in plastic and stored at room temperature (25 ± 5°C) and relative humidity (60 ± 5%), considering real manufacturing conditions. Table 1 summarizes the material composition of each CEB made.

Characterization of the samples

The tests were conducted in a laboratory at a room temperature of 23 ± 5°C and a relative humidity of 60 ± 5%. The pH was measured at a 1:5 ratio , employing a Mettler Toledo S210 pH meter. TG/DTG analysis was performed using a Nabertherm furnace model B400/B410, with the temperature ranging from 30°C to 950°C at a heating rate of 10°C/min, with approximately 30 g of recycled sand properly dried in a ventilated oven at 105°C used for the analysis.

The axial compressive strength of the specimens was determined in accordance with European standard NF EN 13286-41 (NF EN, 2005a). For each treatment, three specimens were systematically tested at different curing time periods (0, 7, 14, 28, and 56 days). The equipment used for the determination of the axial compressive strength was a 100 kN Zwick/Roell Z100 press, operating at a constant loading speed calibrated at 20 N/s, corresponding to 0.01 MPa/s. To analyze their mass loss during storage, the blocks were weighed after fabrication and before the compressive strength testing.

Each treatment involved testing three samples to determine diametral tensile strength, using a 100 kN Zwick-Roell Z100 Universal Testing Machine, at a strain rate of 1.5 mm min^{-1} and a gauge length of 10 mm. This was followed by a carbonation test conducted at 58 days, following the principles outlined in European standard NF EN 14630 (NF EN, 2006). Linear regression analyses were performed using Microsoft Excel®.

RESULTS AND DISCUSSION

Characterization of CDW

The granulometric analysis of the CDW (Figure 4) revealed that more than 60% of the material passed through the 1.00 mm sieve and 50% passed through the 0.5 mm sieve.

The CDW used in this study showed fewer fines compared to the material analyzed by Hou *et al.* (2023), with approximately 50% of the material passing through the 1.00 mm mesh and 30% through the 0.5 mm mesh. Therefore, the granulometry of the material is not completely homogeneous, and, depending on its collection, may present differences in its characterization. The surface dry specific density of the CDW (Table 2) was consistent with values reported in the literature (Souza; Rudnick; Lukiantchuki, 2020; Hou *et al.*, 2023).

In this study, the CDW sample showed a $CaCO_3$ content of 18.54 ± 2.11, which is comparable to the 21.42 wt% of CaO reported by Garzón *et al.* (2022). The measured pH of the CDW was 7.97 ± 0.09, which revealed that the material had already undergone carbonation . This value is lower when compared to values from the literature––for example, a pH of 10.5 by Souza, Rudnick and Lukiantchuki (2020) and values of 9.72 and 11.03 for two CDW samples analyzed by Artuso and Lukiantchuki (2019). These authors related the low pH values with the carbonation of small fractions of concrete and cementitious mortars.

Characterization of compressed earth blocks with CDW

Physical characterization

The water content of CEBs used in this study was 9%, which falls within the commonly used range of 5–10% in the literature, according to Abid *et al.* (2022). In addition, the water content values of CEBs were close to 9.5 and 10% when using 15 and 10% of recycled aggregates, as reported by Bogas, Silva and Gomes (2019) and Hou *et al.* (2023), respectively. Some of the CEB specimens used in this study showed defects such as small cracks or pecked edges after demolding, as shown in Figure 5. Defects, such as drying cracks, were also identified in CEB specimens stabilized with 2 and 4 wt% ovalbumin , as reported by Ouedraogo *et al.* (2021). The authors attributed the defects to montmorillonite soil's swelling and shrinkage behavior combined with the ovalbumin's surfactant effect, which acted as a repulsive force for the wet mixture.

Sample CEB-0 exhibited greater crumbling during demolding and after the removal of the plastic wrapping compared to sample SCEB-4 (Figure 6). Therefore, 4% cement content provided the best integrity of the specimens. The storage of the specimens with plastic wrapping did not yield the desired benefits, according to the analysis of mass loss as a function of curing time (Figure 6a).

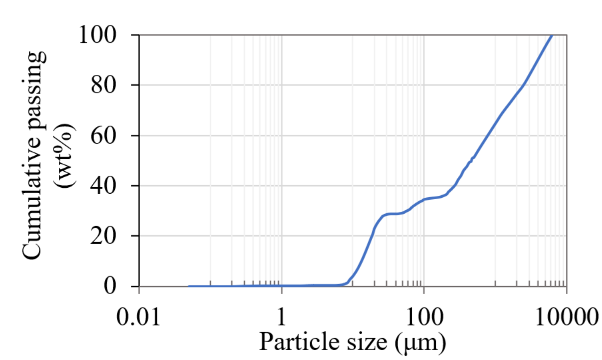

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Figure 4 – Granulometric analysis of the CDW (0/6.3 mm).

Table 1 – Compositions of each Ø50×50 mm CEB.

Mixture composition	CDW (g)	CEM III/A (g)	Water (g)	Compactness (C)
CEB-0	198.2	0	17.8	0.845
SCEB-4	191.9	7.7	18.0	0.843

Source: The authors.

Table 2 – Characterization of CDW.

	MBV (-)	ρ_a (g cm^{-3})	ρ (g cm^{-3})	C (-)	$CaCO_3$ (%)	pH
CDW	0.17	1.54 (± 0.02)	2.39 (± 0.02)	0.65 (± 0.01)	18.54 (± 2.11)	7.97 (± 0.09)

MBV: methylene blue adsorption value; ρ_a: apparent density (bulk density); ρ: surface dry specific density; C: compactness.
Source: The authors.

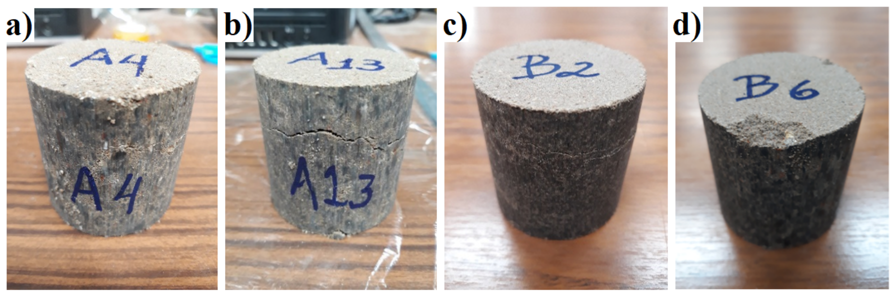

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Figure 5 – CEB-0 samples with defects such as (a) brittle edges and (b) cracks, and SCEB-4 samples with defects such as (c) cracks and (d) broken edges.

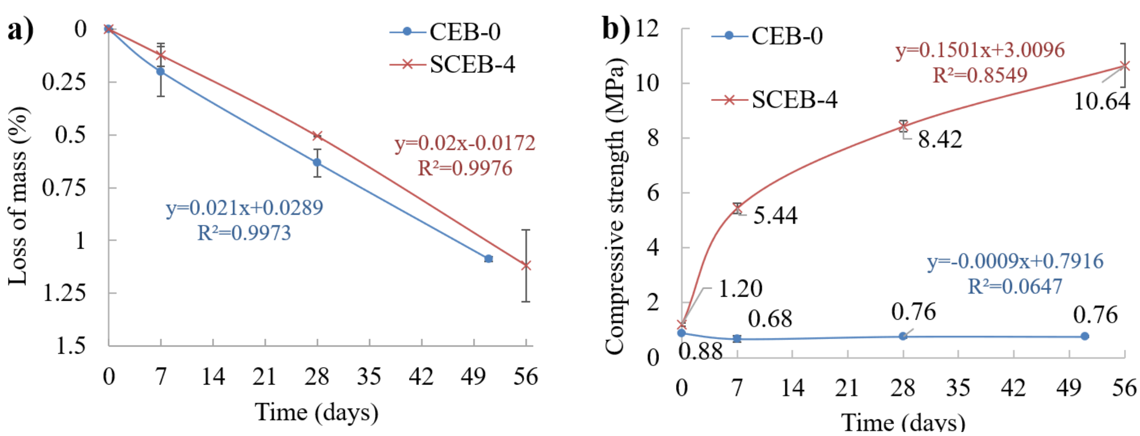

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Figure 6 – Mass loss of samples CEB-0 and SCEB-4 as (a) a function of curing time and (b) the compressive strength of samples versus curing time.

The mass loss of samples CEB-0 and SCEB-4 was similar over time, reaching values of 1.09% at 51 days and 1.12% at 56 days for each treatment, respectively (Figure 6a). Despite the use of plastic wrapping, the samples exhibited relatively low mass loss, indicating that the storage medium was not fully sealed. In other words, the plastic wrapping was not entirely endogenous, leading to moisture loss over time.

Mechanical strength

The compressive strength (f_b) of sample CEB-0 remained relatively the same over time (Figure 6b), with little variations, demonstrating that the material requires the addition of clay or some binder. This corroborates the result of MBV (Table 2), which shows that the CDW has a low amount of clay in its composition. In contrast, sample SCEB-4 showed a growing resistance over time, reaching up to 10.64 (± 0.79) MPa at 56 days (Figure 6b). Figure 7 depicts a comparison between the compressive strength results of cement-incorporated CEBs and SCEBs from this study and those reported in the literature, measured at approximately 28 days.

The performance of sample CEB-0 was comparable to that of CEBs made with soil having no cement content, as reported by Kidari and Tilioua (2024). However, the compressive strength of CEB-0 was lower than that of type BTC 20 and also lower than CEBs with soil having no stabilizers, as reported in the literature (Bogas; Silva; Gomes, 2019; Ouedraogo *et al.*, 2021; Morselli *et al.*, 2024) (Figure 7). In contrast, sample SCEB-4 exhibited higher compressive strength compared to the SCEB with 4% cement from Kidari and Tilioua (2024), as well as to types BTC 20, BTC 40, and, even BTC 60. Its performance was comparable to that reported by Ouedraogo *et al.* (2021), but lower than the CEB with

5% cement, used by Benzerara *et al.* (2021). However, sample SCEB-4 exhibited better performance compared to SCEBs produced by Souza *et al.* (2021), which incorporated 6% and 12% cement, respectively, and also those reported by Bogas, Silva and Gomes (2019) using 8% cement.

Sample SCEB-4 demonstrated promising average compressive strength results compared to CEB type BTC 60––a commercial, standardized, and widely used block in France (NF EN, 2001)––and those of CEB type BTC 60 defined by the Colombian standard NTC 5324 (ICONTEC, 2004). While CEB type BTC 60 had a compressive strength (*fb*) of 6 MPa, sample SCEB-4 exhibited values of 8.42 MPa at 28 days and 10.64 MPa at 56 days (Figure 6b). Hence, it is evidenced from the findings that SCEB-4 complies with the Brazilian standards for soil-cement bricks or blocks (ABNT, 2012a; 2012b), satisfying the requirement of a minimum average mechanical compressive strength of 2.0 MPa, at 7 days.

Table 3 presents a comparison of the diametral tensile strength results for the CEB-0 and SCEB-4 samples from this study, complying with French standards, and those results found in the literature for CEBs and SCEBs incorporating CDW.

Due to the brittle nature of sample CEB-0, the diametral tensile strength test could not be performed. This suggests that replacing raw earth with CDW is alone not sufficient and hence it requires some stabilizer to meet the mechanical performance requirements. With a substitution of 15% soil in CDW, Bogas, Silva and Gomes (2019) produced a CEB that allowed for the execution of the test, demonstrating a diametrical tensile strength of 0.08 MPa at 28 days.

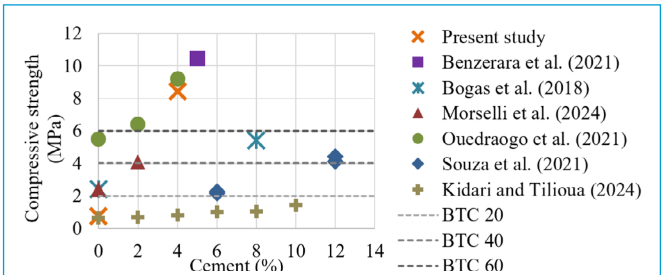

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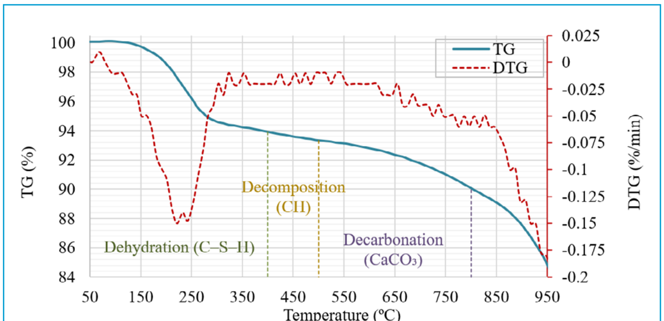
Figure 7 – Comparison between the compressive strength results of cement-incorporated CEBs and SCEBs from this study and those reported in the literature, measured at 28 days.

Sample SCEB-4 exhibited a diametrical tensile strength of 0.91 (± 0.09) MPa at 58 days, which is above the minimum value of 0.6 MPa for evaluating the average tensile strength of CEB type BTC 60 as specified by the French standard NF EN (2001). The diametrical tensile strength of SCEB-4 was superior compared to values reported in the literature, such as the 0.149 MPa obtained for an SCEB using 2% cement developed by Morselli *et al.* (2024), and the 0.68 MPa as reported by Bogas, Silva and Gomes (2019) for SCEBs using 4% cement, 4% lime, and 15% CDW. However, the diametrical tensile strength of sample SCEB-4 was lower than the 1.19 MPa achieved by an SCEB using 8% cement and 15% CDW as also reported by Bogas, Silva and Gomes (2019).

Thermogravimetry test

Sample SCEB-4 demonstrated a 15.56% of loss to fire when subjected to temperatures up to 950°C, as shown in the TG/DTG analysis (Figure 8). The loss attributed to the dehydration (up to 400°C) of the cementitious matrix was 6.11% (Figure 8), corresponding to the loss of intergranular water and related to the dehydration of hydrated calcium silicates (C–S–H), hydrated calcium monosulfate (AFm), ettringite (Aft), and gypsum ($CaSO_4.2H_2O$). From 400 to 500°C, the decomposition of portlandite (CH) in free lime ($Ca(OH)_2$) was 0.57% and from 500 to 800°C, the decarbonation of calcite ($CaCO_3 \rightarrow CaO+CO_2$) was 3.37%.

The increase in compressive strength observed in the SCEB-4 samples over time is in line with the TG/DTG results (Figure 8), where there was a



Source: The authors.

Figure 8 – Graph depicting the thermogravimetric (TG) and derived thermogravimetric (DTG) analysis of the sample SCEB-4.

Table 3 – Comparison of the diametrical tensile strength results for the CEB-0 and SCEB-4 samples from this study and those reported in the literature.

Reference	Cement (%)	Lime (%)	CDW (%)	Tensile strength (MPa)
CEB-0	0	0	100	NA*
SCEB-4	4	0	96	0.91 (± 0.09)
Morselli *et al.* (2024)	2	0	98	0.149
Bogas, Silva and Gomes (2019)	0	0	15	0.08
Bogas, Silva and Gomes (2019)	4	4	15	0.68
Bogas, Silva and Gomes (2019)	8	0	15	1.19
BTC 20 (NF EN, 2001)	-	-	-	0.2
BTC 40 (NF EN, 2001)	-	-	-	0.4
BTC 60 (NF EN, 2001)	-	-	-	0.6

*NA: Not allowed.
Source: The authors.

considerable loss of mass, related to the dehydration of C–S–H, which are responsible for conferring mechanical strength to the concrete. Compared to the TG/DTG analysis of CDW alone (Figure 1), the SCEB-4 samples showed greater losses of mass on fire, loss in the dehydration of C–S–H, and loss of mass on the decomposition of portlandite and calcite, confirming the improvement of mechanical performance with the cementitious reactions that occurred from the addition of only 4% cement.

Carbonation and pH tests

Figure 9 shows the images of the specimens before and after the carbonation test, while Table 4 shows the corresponding pH values. At 51 days, the pH value of sample CEB-0 (Table 4) closely matched that of the CDW (Table 2), obtained before the manufacturing of the bricks. The CDW had already undergone carbonation before the manufacturing of the bricks, according to its pH value of 7.97 (± 0.09). This corroborates with the colorless appearance of sample CEB-0 following the phenolphthalein test, as shown in Figure 9. On the other hand, the pH of SCEB-4 (Table 4) was higher than that of CEB-0, with a magenta coloration, indicating that it had not yet undergone carbonation. Also in Figure 9, after the carbonation test, discolored parts are observed in sample SCEB-4 , indicating carbonated parts, which can be attributed to the oxidation during the storage of the block. This suggests that the storage form was not completely endogenous, as proposed. These findings are consistent with the results of mass loss (Figure 7), indicating a loss of moisture over time.

According to Hou *et al.* (2023), carbonation has been known to reduce the carbon footprint of the construction sector, as cementitious materials can mineralize atmospheric CO_2. Therefore, the recycling of CDW, an already carbonated material, is favorable to the environment, not only by reducing its improper disposal and consuming natural resources but also by reducing atmospheric CO_2.

Perspectives and feasibility of manufacturing blocks with waste

Latha and Murugesan (2024) reported that the construction costs associated with SCEBs produced using municipal solid waste incinerator ash and sisal fiber were 12.24% higher than those of bricks made with annealed clay. However, in the case of large-scale use, the costs would be reduced. However, López-Rebollo *et al.* (2024) performed an economic feasibility analysis on four types of CEBs developed using different stabilizers and found that the blocks manufactured were among the most cost-effective materials. Compared to conventional materials, the developed CEBs were 32% cheaper than masonry blocks, 38% cheaper than adobe bricks, and 94% cheaper than conventional bricks.

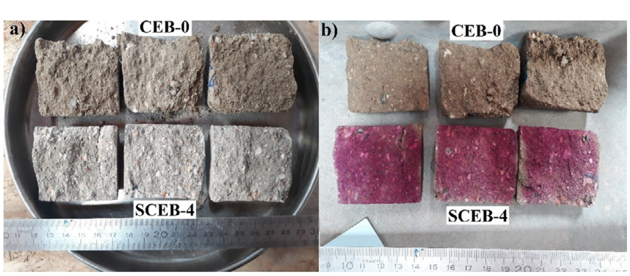
The absence of specific regulations governing the production, commercialization, and utilization of CEBs presents a significant challenge to their widespread adoption. In countries such as Argentina, for example, the lack of product quality certification contributes to a lack of technological knowledge and generates difficulties in market acceptance (Dorado; Cabrera; Rolón, 2022). In addition, studies on the sizing, curing, and conditioning of SCEBs are also scarce, whereas studies on the stabilization of cement blocks are more common (Ouedraogo *et al.*, 2020). While studies on the technical feasibility and durability of sustainable SCEBs are more abundant in the literature, studies related to the economic feasibility of their production remain relatively scarce.

Future research could be continued on the long-term analysis of the durability, mechanical strength, and resistance of blocks to environmental conditions, as well as on the economic feasibility of their large-scale production. The manufacturing of SCEB-4 on a large scale would enable the introduction of economically competitive, sustainable products on the market, with their mechanical performance equal to or superior to that of conventional alternatives.

Table 4 – pH values of samples CEB-0, SCEB-4, and water.

	CEB-0	SCEB-4	Water
pH	8.05 (± 0.02)	9.31 (± 0.61)	7.19 (± 0.56)

Source: The authors.



Source: The authors.

Figure 9 – Images of the specimens (a) before and (b) after the carbonation test.

CONCLUSIONS

Considering the scarcity of research focused on the manufacturing of high-performance, sustainable bricks with greater mechanical strength––using CDW instead of raw earth and reducing the consumption of hydraulic binders––this study demonstrates, with the help of SCEB-4, that it is possible to obtain compressed bricks incorporating CDW and only 4% cement. These blocks can replace CEB types BTC 20, BTC 40 and, even BTC 60, surpassing their nominal resistance.

Furthermore, the use of CDW in the manufacturing of SCEBs is environmentally beneficial. It even promotes the recycling of waste, reduces its improper disposal, and decreases the consumption of non-renewable natural resources. The carbonation of CDW also contributes to reducing the carbon footprint by mineralizing atmospheric CO_2, making SCEBs a sustainable alternative for environmental management and construction activities.

AUTHORS' CONTRIBUTIONS

Morselli, L.B.G.A: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft. Quadro, M.S.: Conceptualization, Supervision, Writing – review & editing. Andreazza, R.: Conceptualization, Supervision, Writing – review & editing.

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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