International Journal of Materials Engineering 2024, 14(1): 1-11
DOI: 10.5923/j.ijme.20241401.01

Adobe Soil-Cement Bricks with Expanded Polystyrene Residue Addition Reinforced with Polyethylene Fibers

Rânfler José Luan Rodrigues Soler, Raul Tadeu Lobato Ferreira*

Earth and Exacts Sciences Institute (ICET), Federal University of Mato Grosso, Barra do Garças, Mato Grosso, Brazil

Abstract The rescue and the improvement of the earth construction techniques are presented as an interesting alternative for the sustainable development of the construction sector, not only for reducing the generation of residues during the construction process, but also for making possible the reuse of the residues generated by the own construction industry and by other sectors. Within this context, the present study proposes an evaluation of soil-cement adobe bricks with the addition of expanded polystyrene residue and reinforced with polyethylene fibers, by checking the compressive strength, shrinkage and cracking of the mixtures, for a curing period 7 days. For that, bricks obtained with incorporation of 0.5%, 0.75% and 1.00% of polyethylene residue and with an incorporation of 0.125%, 0.25% and 0.50% of expanded polystyrene residue were obtained, with the purpose of analyzing the effect of each addition, relating the results obtained to the physical character-istics of the proposed materials. The expanded polystyrene residue incorporation in the soil-cement matrix promoted losses of resistance to simple (uniaxial) compression, while the polyethylene fibers incorporation promoted strength gains, and neutralized the retraction and cracking of the soil-cement mixture. A simultaneous incorporation of the two residues shown to be ad-vantageous resulting in a lighter, more resistant brick with less potential for shrinkage.

Keywords Raw brick, Compressive Strength, Earth construction

1. Introduction

The macrocomplex of the construction industry is the main generator of waste in society. According to data from the Brazilian Association of Public Cleaning and Special Waste Companies, over 48 million tons of construction and demolition waste (CDW) were collected in Brazil in 2021 [1]. Despite a significant portion of these materials being recycled, a considerable amount is degrading in the environment, releasing carbon dioxide (CO_2), polluting rivers and seas, occupying space in sanitary landfills. Additionally, some waste releases harmful substances to human health [2].

Furthermore, the construction sector is a major consumer of natural raw materials. It is estimated that about 50% of the total natural resources consumed by society are used by the construction industry. This significant environmental impact has led several countries to adopt specific environmental policies for the sector. Among these policies, the reuse of resources, the use of renewable resources, reduction of resource consumption, and environmental protection are emphasized. The incorporation of waste into material production can reduce energy consumption and transportation distances of raw materials. Moreover, the incorporation of waste can enable the production of materials with improved technical characteristics in various areas [3-7].

The final disposal of waste is one of the major problems faced by the world today. Therefore, it is interesting to find ways to incorporate waste into the construction process, aiming not only to minimize the impacts generated by the construction industry but also to address issues related to solid waste generation in general.

Current consumption patterns promote the excessive generation of waste, causing both social and environmental problems [8]. Globalization is one of the factors that most influences consumers to buy excessively. With each purchase, a new package enters circulation, and if discarded improperly, it leads to accumulations and negative impacts on the environment. Plastic bags easily spread in the environment, causing a series of problems. The drainage network is one of the main ways wastes are conveyed, and combined with unsustainable consumption patterns, it favors the accumulation of package in drainage devices (curbside drains, storm drains, major stormwater drains, etc.), which can subsequently lead to flooding, causing problems for society and the urban landscape [9].

The amount of plastic waste found in municipal solid waste can vary from 7 to 30%. Despite the increase in Brazilian plastic recycling rates, only about 32% of Brazilian municipalities has an implemented selective collection

* Corresponding author:
raul.ferreira@ufmt.br (Raul Tadeu Lobato Ferreira)
Received: Jan. 1, 2024; Accepted: Jan. 22, 2024; Published: Jan. 27, 2024
Published online at http://journal.sapub.org/ijme

system, according to a 2023 survey by the Business Commitment for Recycling (CEMPRE) [10]. Plastic waste in landfills and the environment, in addition to the visual impact, can release toxic substances such as plasticizers and other additives. After disposal, landfilling is the least favorable option, with reuse, recycling, and incineration being suitable disposal possibilities [11].

Incineration involves burning and decharacterizing waste, allowing a significant reduction in volume. However, it is a process that requires high investments and produces gases from the combustion of waste, potentially hazardous to both human health and the greenhouse effect [12]. According to Vanapalli et al. [13], burning plastic waste produces toxic and carcinogenic gases. The most appropriate form of plastic reuse is recycling, with mechanical recycling being the most widely used worldwide [14,15].

Expanded polystyrene (EPS) is a material composed of 98% air and only 2% carbon and hydrogen. Although it does not chemically contaminate soil, water, or air, it is a chemically inert, non-biodegradable material that becomes an environmental problem if not recycled. Therefore, the reuse of expanded polystyrene becomes a valuable sustainable measure [16,17].

Sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their own needs [18]. However, the achievement of sustainable development requires transformative changes in the construction industry. The construction sector generates environmental impacts due to the high consumption of natural resources and energy in the production and transportation of materials, as well in the improper disposal of waste and packaging on construction sites, which often occurs inadequately [19].

The quantity of waste generated by construction processes is a daily concern, given the numerous problems caused by the accumulation of debris. In an effort to promote sustainable development, some professionals and construction companies have sought to use sustainable construction techniques to minimize the environmental impacts caused by the sector. In this context, earth constructions, specifically adobe bricks, also known as raw earth bricks, allow the reuse of these materials, and from an economic perspective, there are significant cost reductions due to abundant and low-cost raw materials. Considering that adobes have a simplified production process and do not require firing, the price becomes even more accessible for both production and the end consumer. Additionally, they provide good thermal and acoustic comfort in buildings [20].

Adobe bricks have great versatility in their composition. Essentially produced from raw earth, other materials can be incorporated to meet specific needs, such as increased strength, lower specific weight, reduced shrinkage, among others. Several studies have been conducted in this field, assessing the adaptability to added materials, as demonstrated by studies conducted by Schweig et al. [21], Santos et al. [22], and Barroso, Novato, and Ferreira [23]. In Brazil, the requirements and test methods for this type of masonry are regulated by the Brazilian Association of Technical Standards (ABNT) through standard NBR 16814 [24].

Aiming to control shrinkage and cracking in soil-cement ecological bricks, this work sought to add polyethylene fibers to the composition. This material, commonly used in packaging that requires high cracking resistance under tensile stress [25], was obtained by processing plastic bags distributed in the common market, which are usually discarded improperly in nature.

To obtain bricks with lower specific weight, EPS particles obtained from the processing of waste of this material were added. As it is mostly composed of air, this material acts as a void incorporator, thus providing a lower weight to the block [26]. Furthermore, the use of sealing construction elements with the incorporation of EPS can contribute to reducing energy consumption for the thermal conditioning of buildings [27]. Therefore, by reusing these materials, the goal was to produce a resistant brick with reduced apparent weight and low tendency to shrinkage and cracking, which can bring significant improvements to the construction of earthen buildings.

2. Material and Methods

The employed methodology aims to assess the effect of incorporating polyethylene fibers and expanded polystyrene waste into soil-cement adobe bricks. For this purpose, different addition contents were proposed to study the incorporation of the waste separately, and subsequently, a mixture with the incorporation of both wastes together. The evaluation of the proposed mixtures was conducted through uniaxial compressive strength tests and shrinkage tests.

2.1. Soil

Table 1. Physical indexes and soil classification by Schweig et al [21]

Granulometry	Fine Sand	66.37%
	Silt + Clay	33.63%
Atterberg limits	Liquid Limit	18%
	Plastic Limit	12%
	Plasticity Index	6%
AASHTO Classification	Group Index	0
	A-2-4 Group	Granular material, characterized as silty sand or clayey

The present study used soil extracted in 2017 from an area near the margins of the road contour connecting BR-070 and BR-158 highways, as well as close to MT-100 highway, located in the municipality of Pontal do Araguaia – MT. After collection, the soil was disaggregated and sieved, discarding the gravel fraction. Schweig et al. [21], using the American Association of State Highway and Transportation Officials (AASHTO) methodology, classified the soil as granular material of class A-2-4 (0), characterized as silty or clayey sand. The results of the characterization tests are presented in Table 1.

2.2. Portland Cement

The binder used in this research to stabilize and improve the chosen soil was Portland cement combined with pozzolan, classified by the Brazilian standard, NBR 16697, as CP II-Z 32 [28]. Considering the soil classification and following the recommended proportions by the Brazilian Portland Cement Association (ABCP), the cement content adopted for the mixtures was 7% relative to the dry mass of the soil [21,29].

2.3. Polyethylene Fibers

The polyethylene fibers were obtained by cutting plastic bags provided by commercial establishments, which would be improperly discarded. The material was collected, cleaned, and sorted based on the similarity of raw materials, as not all plastic bags are made from the same type of polyethylene. For this research, Polyethylene High Density (HDPE) - Class 2 bags were chosen, as they are the most common among the packaging available in commercial establishments. In total, approximately 1.1 kg of processed polyethylene was used. Fibers with dimensions of 3 cm in width by 10 cm in length were produced. These dimensions are recommended in the literature as an ideal size for incorporation into adobe bricks [30]. The appearance of the produced fibers is presented in Figure 1.

Figure 1. Polyethylene Fibers

2.4. Expanded Polystyrene Waste

The expanded polystyrene waste was originated from packaging of household appliances that would be improperly discarded. The packaging was collected, cleaned, and processed using a common blender. In order to achieve good particle dispersion, the waste processing was done in several stages with small quantities, resulting in the material shown in Figure 2. In total, approximately 350 grams of processed expanded polystyrene was used. For the characterization of the obtained material, a granulometric analysis was conducted by washing a processed waste sample through sieves with openings of 19.00, 9.50, 4.75, 2.36, 2.00, 1.40, and 0.30 mm.

Figure 2. Processed expanded polystyrene waste being mixed with soil

2.5. Adobe Brick Confection

Four groups of adobe bricks were manufactured, with the first group consisting of soil-cement blocks, the second group of soil-cement blocks with the addition of polyethylene fibers, and the third group of soil-cement blocks with the addition of expanded polystyrene waste. The fourth group was produced based on the content of each waste (polyethylene and EPS) that individually showed the best performance in the second and third group. These were combined to create a fourth group of soil-cement blocks with the addition of EPS waste and reinforced with polyethylene fibers. The produced mixtures were subjected to uniaxial compressive strength tests and shrinkage tests.

Table 2. Composition of the mixtures

Nomenclature	Combinações		
	Cement Content (%)	EPS Content (%)	Polyethylene Fiber Content (%)
Soil-cement	7.0	-	-
E-0.125	7.0	0.125	-
E-0.25	7.0	0.25	-
E-0.50	7.0	0.50	-
P-0.50	7.0	-	0.50
P-0.75	7.0	-	0.75
P-1.00	7.0	-	1.00
EPS + polyethylene fibers	7.0	optimum content	optimum content

The adobe bricks production process involves initially moistening the walls of the concrete mixer with water, adding the pre-mixed soil, cement, and waste blend, and finally, gradually adding water to the mixture until a plastic consistency is achieved [31]. It is emphasized that the amount of water used in the production of a mixture was replicated in subsequent productions, when necessary, to ensure the same moisture for all blocks of the same mixture.

All waste and cement content were considered relative to the mass of dry soil. The produced mixtures and their respective compositions are shown in Table 2.

The bricks were molded on the ground covered with a tarpaulin using an open mold with dimensions of 12 cm in width, 24 cm in length, and 7 cm in height, with the capacity to produce two blocks simultaneously. The molding process, illustrated in Figure 3, involves placing small amounts of the prepared mixture in the mold, which should be previously coated with lubricating oil to facilitate demolding. Care should be taken during the process to ensure that no void spaces (not occupied by the mass) are left in the mold. After completely filling the mold, the blocks are leveled by removing excess mixture, leaving the upper face of the block flat. Subsequently, the mold is lifted vertically for demolding the blocks.

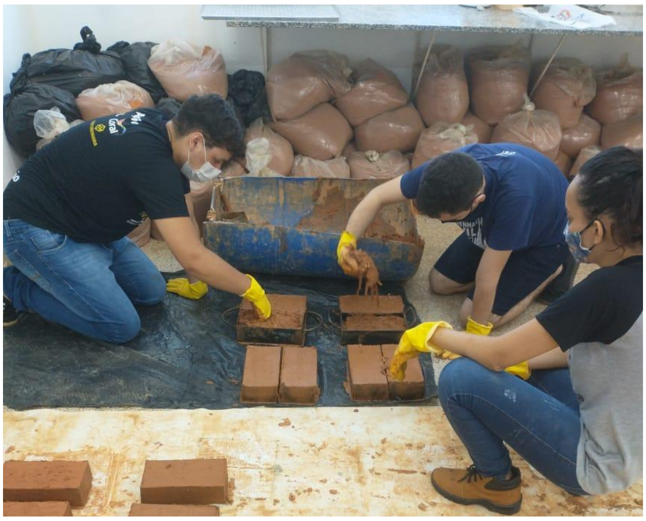

Figure 3. Adobe brick confection

The curing of the bricks was carried out in the open air, at room temperature, in a location protected from the elements, for a period of seven days. At the end of the curing period, the mass and volume of the specimens were measured to analyze the density of the blocks later on. The density of the blocks was calculated by dividing the mass by the volume.

2.6. Uniaxial Compressive Strength Test

The uniaxial compression strength test was conducted with the aim of verifying the effect that the addition of residues has on the compression strength of the soil-cement adobe brick compared to bricks without any type of addition. The preparation of the test specimens involved mortaring the upper face of the brick with cement mortar after a curing period of 7 days. As proposed by Silva [32] and Schweig et al. [21], the mortar produced for this purpose has a ratio of 1:2 (one part cement and two parts sand), with a moisture content of 25%, and is applied with a maximum thickness of 3 mm. This proce-dure aimed to parallelize the compressed faces. In Figure 4, the appearance of the blocks after capping is presented.

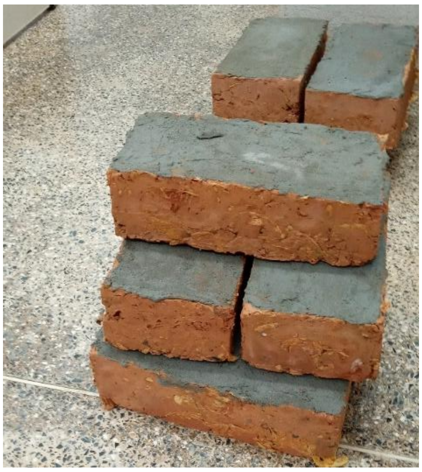

Figure 4. Appearance of the bricks after mortaring

After a 24-hour curing period for the mortar, the blocks were placed centrally on the compression testing machine's plate. Two metal plates were used to transfer the load to the specimen uniformly. The samples underwent compressive strength testing at a deformation rate of 50 mm/min. In this procedure, 5 blocks from each mixture were evaluated after a curing period of 7 days.

The compressive strength of the blocks was also evaluated under critical conditions. After 7 days of curing, five blocks from each mixture were mortared and subjected to 24 hours of immersion in water at room temperature, following mortar curing. After the water immersion period, the blocks were dried superficially and subjected to the uniaxial compressive strength test. In this procedure, metal plates were also used for the uniform transfer of the load applied by the testing machine, and the deformation rate was maintained at 50 mm/min. In this situation, the average compressive strength of the blocks in each group was determined by the simple average of five determinations.

The compressive strength values were statistically analyzed using analysis of variance (ANOVA), Tukey multiple comparison test, and Student t-test using the free software Paleontological Statistics (PAST) version 3.22. Within the same group of blocks, ANOVA was performed to assess the existence of significant differences among mixtures with different residue contents. The Tukey test was used to identify which compositions showed significant differences.

The Student t-test, which was conducted assuming different variances among the mixtures, was applied to verify the existence of a significant difference between the average compressive strength of blocks subjected to and not subjected to the water immersion period. Since the hypothesis is based on the difference of means, the data analysis for this statistical treatment was conducted considering a two-tailed test.

In the analysis of the existence of significant differences between compositions, two hypotheses were considered: the null hypothesis, which assumes no difference between the means, and the alternative hypothesis, where not all means are equal. In all analyses, a significance level (p) of 5% was deemed satisfactory. If $p \leq 5\%$, the null hypothesis is rejected, indicating significant difference between the means, and if $p > 5\%$, there are no significant differences.

2.7. Shrinkage Test

The shrinkage test was conducted with mixtures containing residue in their composition, following the procedure proposed by the Research and Development Center (CEPED) [31]. In this test, a mixture is considered suitable when, upon analysis of the results, it shows no cracks or shrinkage greater than 2 centimeters. The procedure involves preparing a plastic-consistency mass, similar to clay, which is placed in the testing box with internal dimensions of 3.5 cm in height, 8.5 cm in width, and 60 cm in length. Figure 5 illustrates the procedure for placing the mixtures in the testing box.

Figure 5. Accommodation of mixtures in the shrinkage test box

After placing the mixture in the testing box, the material remains at rest, protected from the elements, for a curing period of 7 days. At the end of this period, the presence of cracks and fissures is checked, and the shrinkage of the material is measured in the direction of the larger dimension of the box, with a precision of 1 mm. In this procedure, fractures with an opening greater than 1 mm were considered cracks, and those with an opening less than 1 mm were considered fissures. The shrinkage value was obtained by summing the averages of three measurements on each side of the box.

3. Results and Discussion

This section presents and discusses the results obtained considering the proposed methodology. Firstly, the results related to bricks with the incorporation of EPS residue are presented, followed by the results related to bricks reinforced with polyethylene fibers. The analysis of these results defines the optimal content for each residue, and finally, the results related to blocks with the addition of EPS residue reinforced with polyethylene fibers are presented.

3.1. Soil-Cement with Addition of EPS Waste

While processing expanded polystyrene, a variation in the particle size was observed. This variation in particle dimensions was evaluated through a granulometric analysis by washing. By weighing the fraction of particles retained on each sieve, it was possible to plot the particle size distribution curve of the residue, as shown in Figure 6. It can be observed that the curve has a vertical development, indicating a uniform gradation.

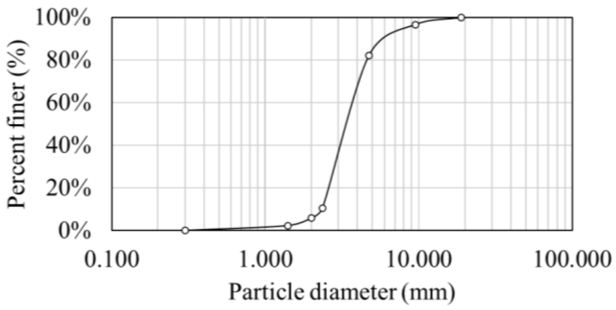

Figure 6. Granulometric curve of expanded polystyrene (EPS) waste

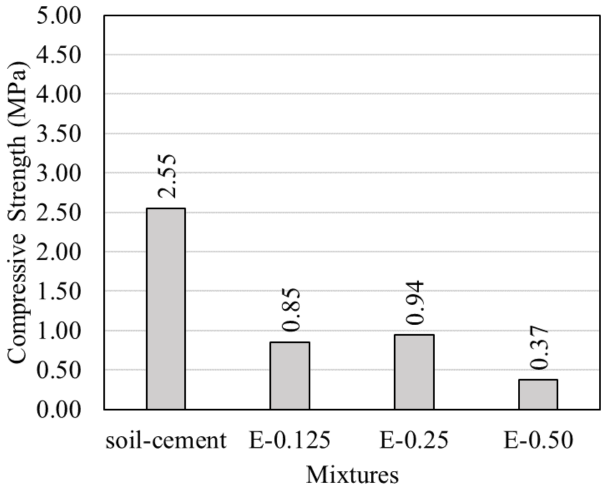

Figure 7. Average compressive strength after 7 days of curing – bricks with EPS

Table 3. Average compressive strength (±standard deviation) – bricks with EPS

Mixtures	Compressive strength (MPa)	Δ (%)
Soil-cement	2.55±0.12	-
E-0.125	0.85±0.06	-67
E-0.25	0.94±0.07	-63
E-0.50	0.37±0.01	-85

Note: Δ (%) is the variation in compressive strength relative to the reference mixture (soil-cement)

The results obtained in the simple compression strength test are presented in Figure 7 and Table 3. Overall, with regard to compression strength, the incorporation of EPS residue was not beneficial. The strength of all compositions containing residue was below the strength of the reference mixture (soil-cement). After 7 days of curing, the mixtures E-0.125, E-0.25, and E-0.50 showed, respectively, a reduction in strength of 67%, 63%, and 85% compared to the strength of soil-cement mixture without residue addition.

With the statistical treatment of the data, it was possible to observe that all mixtures with EPS residue differ significantly from the reference mixture (soil-cement). The E-0.125 and E-0.25 mixtures do not have significant differences between them, while the E-0.50 mixture differs significantly from all others.

The average compression strength values of the bricks subjected to 24 hours of water immersion are presented in Figure 8 and Table 4. Based on the results presented, a decrease in strength can be observed after immersion.

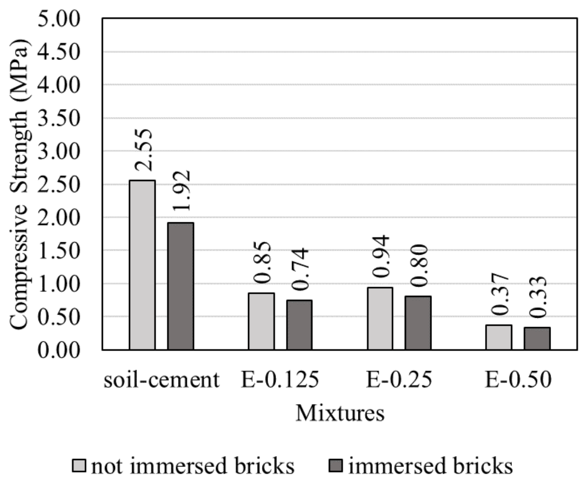

Figure 8. Average compressive strength after immersion in water - bricks with EPS

Table 4. Average compressive strength (±standard deviation) – bricks with EPS after immersion

Mixtures	Compressive strength (MPa)	Compressive strength after immersion in water (MPa)	Δi (%)
Soil-cement	2.55±0.12	1.92±0.26	-25
E-0.125	0.85±0.06	0.74±0.06	-13
E-0.25	0.94±0.07	0.80±0.02	-15
E-0.50	0.37±0.01	0.33±0.02	-11

Note: Δi (%) is the variation in the compressive strength of the bricks immersed relative to the bricks not underwent to immersion

Basing the analysis on the reference mixture (soil-cement), it is noticeable that mixtures with EPS residue showed a low reduction in strength after 24 hours of water immersion. While the reference mixture exhibited a reduction in simple compression strength of 25%, the E-0.125, E-0.25, and E-0.50 mixtures showed reductions of 13%, 15%, and 11%, respectively.

With the statistical treatment of the data, it was observed that all losses in simple compression strength after 24 hours of immersion are significant ($p < 0.05$). After water immersion, the reference mixture and E-0.50 mixture, differs significantly from all other mixtures, while the E-0.125 and E-0.25 mixtures do not show significant differences between them.

According to the results obtained, it is observed that the addition of EPS residues affected the compression strength of the bricks. The mixture containing the highest content of expanded polystyrene (0.50%) showed the lowest resistance value and the greatest loss of strength compared to the reference mixture. The bricks made with the E-0.50 mixture, whether subjected or not to the water immersion process, showed a loss of strength in relation to the reference mixture of 83% and 85%, respectively.

The shrinkage test using the box method did not yield satisfactory results in all cases. The E-0.50 mixture exhibited a crack with an opening of approximately 3 mm, the E-0.25 mixture showed a crack with an opening around 1 mm, and finally, the E-0.125 mixture presented a fissure, with the opening unable to be determined. The appearance of the mixtures at the end of the 7-day curing period is shown in Figure 9.

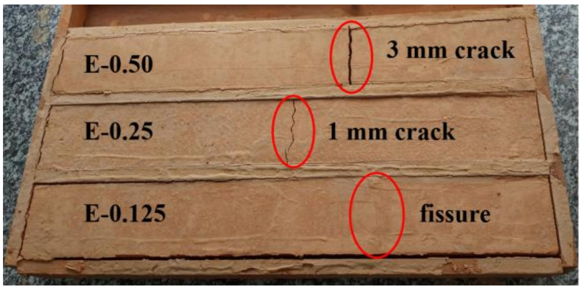

Figure 9. Shrinkage test: soil-cement with EPS residue

Due to the presence of cracks, the E-0.25 and E-0.50 mixtures are considered unsuitable for use in construction elements [31]. With an average shrinkage (6 mm) below the maximum allowable value, the E-0.125 mixture has the potential for use in construction elements. Since expanded polystyrene residue is a type of aggregate, it was not expected to contribute to the reduction of cracks resulting from water loss to the environment.

The incorporation of expanded polystyrene residue aimed primarily at reducing the weight of the blocks, which is a factor of great relevance for their use in construction. The lighter the load from masonry, the lower the cost of the structure. In this regard, the density of the reference blocks was evaluated in comparison with the blocks from the E-0.125, E-0.25, and E-0.50 mixtures. The results are presented in Figure 10 and Table 5. A reduction in block density is noticeable with an increase in the residue content, reaching a reduction of 36% for the highest studied EPS residue content.

Table 5. Average density (±standard deviation) – bricks with EPS

Mixtures	Density (g/cm³)	Δ (%)
Soil-cement	1.81±0.05	-
E-0.125	1.55±0.05	-15
E-0.25	1.53±0.03	-16
E-0.50	1.16±0.02	-36

Note: Δ (%) is the variation in density in relation to the reference mixture (soil-cement)

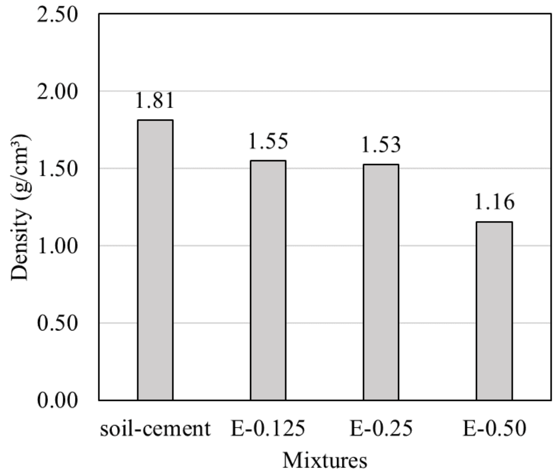

Figure 10. Average density of bricks with EPS after 7 days of curing

The reduction in brick density is due to the fact that expanded polystyrene is composed of 98% air, causing the density of the composites to decrease as the EPS content in the composition increases. This fact benefits not only the reduction of loads on the structure but also aspects related to thermal and acoustic comfort. On the other hand, this incorporation of air through EPS in soil-cement mixtures has brought negative consequences related to the mechanical performance of the bricks, reducing the compressive strength with an increase in the residue content in the mixture.

Considering all factors, the 0.125% content of expanded polystyrene is defined as the optimal content for making blocks with the combination of EPS and polyethylene fibers. This decision takes into account the effect of adding EPS to the soil-cement matrix, considering that there are no significant differences between the E-0.125 and E-0.25 mixtures. Additionally, the blocks from the E-0.125 mixture have a 15% lower density than the reference blocks, and in the shrinkage test, this mixture exhibited the best performance.

3.2. Soil-Cement with Addition of Polyethylene Fibers

The average values of uniaxial compressive strength for soil-cement bricks reinforced with polyethylene fibers are presented in Figure 11 and Table 6. Overall, it is observed that the addition of fibers resulted in an increase in the compression strength of the bricks.

Table 6. Average compressive strength (±standard deviation) – bricks with polyethylene fibers

Mixtures	Compressive strength (MPa)	Δ (%)
Soil-cement	2.55±0.12	-
P-0.50	3.12±0.33	22
P-0.75	3.83±0.29	50
P-1.00	3.74±0.39	46

Note: Δ (%) is the variation in strength relative to the reference mixture (soil-cement)

With the statistical treatment of the data, it was found that the gain in strength concerning the reference mixture with the incorporation of polyethylene fibers was significant for all mixtures. Furthermore, the P-0.75 and P-1.00 mixtures do not differ significantly from each other, however, the P-0.50 mixture shows a significant difference compared to these two mixtures.

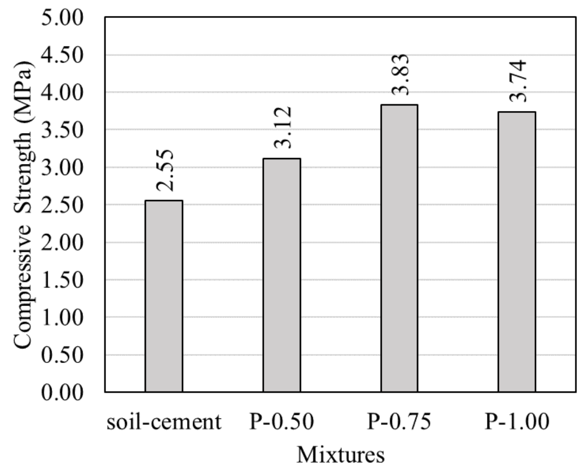

Figure 11. Average compressive strength after 7 days of curing – bricks with polyethylene fibers

In Figure 12 and Table 7, the average values of uniaxial compressive strength of the blocks after 24 hours of water immersion are presented, compared to the strength values of the blocks not subjected to this process.

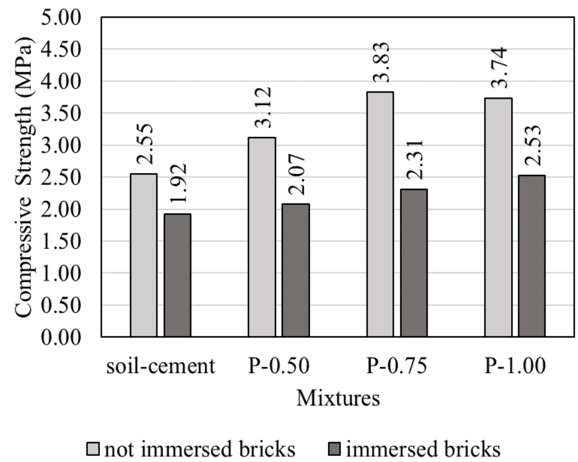

Figure 12. Average compressive strength after immersion in water - bricks with polyethylene fibers

Table 7. Average compressive strength (±standard deviation) – bricks with polyethylene fibers after immersion

Mixtures	Compressive strength (MPa)	Compressive strength after immersion in water (MPa)	Δi (%)
Soil-cement	2.55±0.12	1.92±0.26	-25
P-0.50	3.12±0.33	2.07±0.26	-33
P-0.75	3.83±0.29	2.31±0.16	-40
P-1.00	3.74±0.39	2.53±0.15	-32

Note: Δi (%) is the variation in the strength of the bricks immersed relative to the bricks not underwent to immersion

Examining the results obtained for this test with blocks subjected to water immersion, a decrease in compression strength is observed: 33% for the P-0.50 mixture, 40% for the P-0.75 mixture, and 32% for the P-1.00 mixture. All these losses in compression strength are significant ($p < 0.05$). After water immersion, except for the P-0.50 mixture, the other mixtures significantly differ from the reference mixture.

In the test, no strength peaks were observed for the blocks reinforced with polyethylene fibers. Throughout the test, even with the maximum displacement of the compression testing machine's plate (25 mm), no reduction in the strength of the blocks was observed. Therefore, the values obtained for mixtures containing polyethylene fibers refer to the strength offered by the block at the moment the limit deformation was reached in the testing machine. This behavior was also observed by Schweig et al. [21] when inserting kraft paper fibers into the soil-cement matrix. As noted by Burbano-Garcia et al. [33], while the fracture of a common adobe is of a brittle nature, the fracture of the adobe with added fibers is ductile, which corresponds to what was observed in the compression strength test.

At the evaluated contents, the incorporation of polyethylene fibers into the soil-cement matrix had a satisfactory effect. The tested samples did not exhibit cracks or fissures along their length, as can be seen in Figure 13.

Figure 13. Shrinkage test: soil-cement with polyethylene fibers

During the measurements of shrinkage in the box, it was not possible to measure longitudinal shrinkage in the P-0.75 and P-1.00 mixtures; therefore, it is considered that these mixtures did not shrink significantly, while the P-0.50 mixture showed an average shrinkage of 2.0 mm. As they did not present cracks and exhibited shrinkage less than 2 cm, all mixtures containing polyethylene fibers have an appropriate behavior, regarding shrinkage, for construction components and elements, according to CEPED [31].

According to Kafodya, Okonta, and Kloukinas [34], in earth construction techniques, the incorporation of fibers aims to reinforce the soil with an internal framework, increasing its strength and distributing the effects of shrinkage and expansion, which was indeed observed in the results obtained in the compressive strength and shrinkage tests.

The average density values for blocks with polyethylene fibers are presented in Figure 14 and Table 8, compared to the average density of reference blocks.

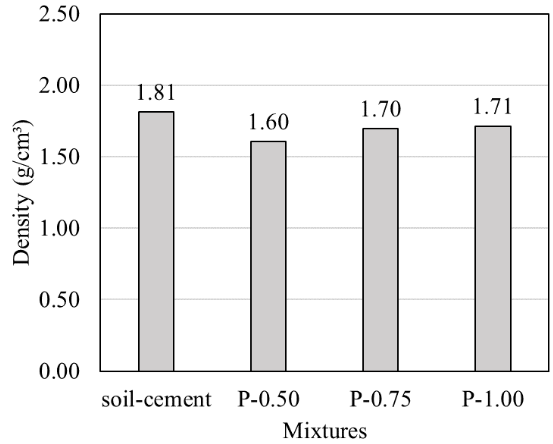

Figure 14. Average density of bricks with polyethylene fibers after 7 days of curing

Table 8. Average density (±standard deviation) – bricks polyethylene fibers

Mixtures	Density (g/cm³)	Δ (%)
Soil-cement	1.81±0.05	-
P-0.50	1.60±0.05	-11
P-0.75	1.70±0.02	-6
P-1.00	1.71±0.01	-5

Note: Δ (%) is the variation in density in relation to the reference mixture (soil-cement)

Based on the presented results, there is little variation in the absolute value of the average density of blocks reinforced with polyethylene fibers compared to the reference blocks (soil-cement). However, it is worth noting that all blocks reinforced with polyethylene fiber have an average density lower than that of the reference mixture, and therefore, the added residue may have increased the material's porosity, albeit insignificantly. Schweig et al. [21] and Barroso, Novato, and Ferreira [23] observed that an increase in fiber content in the composition increases the water absorption capacity of the adobe bricks, which may be related to the material's porosity and, consequently, its density.

Considering the studied contents and the presented results, it is understood that the optimal content for the production of blocks with the simultaneous incorporation of residues is 1.0% of polyethylene fibers. This understanding takes into account that, among the studied mixtures, the P-1.00 mixture allows for the highest incorporation of plastic residue, meets the CEPED shrinkage criterion, and exhibits a simple compression strength superior to that of the reference mixture.

3.3. Soil-Cement with Addition of EPS Waste Reinforced with Polyethylene Fibers

The average values of uniaxial compressive strength for soil-cement blocks with the addition of EPS residue reinforced with polyethylene fibers, both immersed and non-immersed in water, are presented in Figure 15 and Table 9. Overall, it is noted that the simultaneous addition of residues was beneficial for the compression strength of the brick, especially in the case without water immersion.

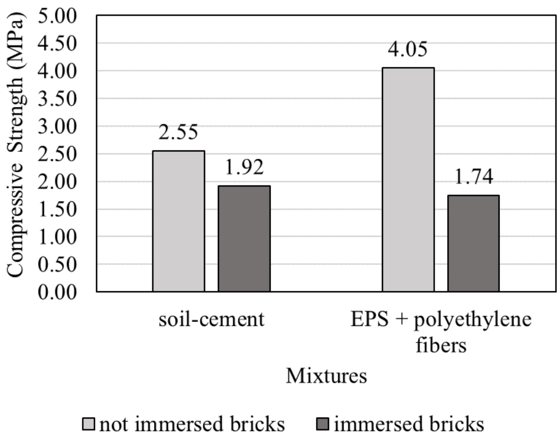

Figure 15. Average compressive strength after immersion in water - bricks with EPS + polyethylene fibers

Table 9. Average compressive strength (±standard deviation) – bricks with EPS + polyethylene fibers after immersion

Mixtures	Compressive strength (MPa)	Compressive strength after immersion in water (MPa)	Δi (%)
Soil-cement	2.55±0.12	1.92±0.26	-25
EPS + polyethylene fibers	4.05±0.18	1.74±0.45	-57

Note: Δi (%) is the variation in the strength of the bricks immersed relative to the bricks not underwent to immersion

The simultaneous incorporation of residues was satisfactory as it promoted a significant gain in strength for blocks not immersed in water ($p < 0.05$). Despite the significant drop in strength after immersion ($p < 0.05$), the strength after immersion of the block containing EPS and polyethylene fibers does not differ significantly from the strength of the reference block (soil-cement) subjected to the same process (they are statistically equal) ($p > 0.05$). The significant loss of strength after water immersion can be attributed to the potential increase in porosity caused by the simultaneous incorporation of residues.

It is noteworthy that bricks with polyethylene fibers and EPS residue exhibited the same behavior as bricks containing only polyethylene fibers when tested, i.e., the maximum displacement of the compression testing machine's plate (25 mm) was reached without observing a peak in strength.

Figure 16. Shrinkage test: soil-cement with EPS + polyethylene fibers

In mixtures with the incorporation of EPS residue, the appearance of cracks and fissures was observed. With the combination of this residue with polyethylene fibers, this problem was resolved, as can be seen in Figure 16. The mixture with polyethylene fibers and EPS residue did not exhibit cracks or fissures, and longitudinal shrinkage was not relevant.

The mixture with EPS residue and polyethylene fibers exhibited an average shrinkage of approximately 2 mm, thus being lower than the maximum allowable recommended by CEPED. As it did not show cracks or fissures, regarding shrinkage, the mixture has suitable behavior for construction components and elements.

In the study conducted by Schweig et al. [21], the authors observed that the incorporation of kraft paper fibers neutralized the shrinkage of the soil-cement mixture. Novato [35], investigating the incorporation of rubber fibers into the same soil-cement matrix, also observed good behavior regarding shrinkage, despite this type of fiber negatively affecting the compression strength of the brick. Similarly, Barroso, Novato, and Ferreira [23] also observed a reduction in the shrinkage of the soil-cement mixture with the incorporation of wood fibers. The authors noted that, despite the benefit regarding shrinkage, an excess of wood fiber adversely affects the compression strength of bricks. In this context, the performance of polyethylene fibers stands out compared to the fibers evaluated by the mentioned authors, as they, whether alone or in association with EPS residue, reduce shrinkage and the occurrence of cracks without compromising the compression strength of the blocks.

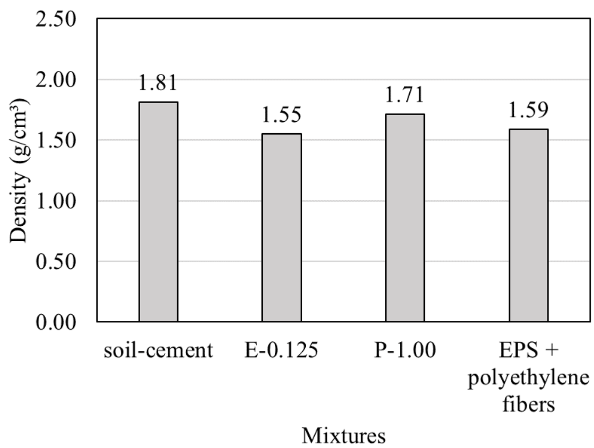

Figure 17. Average density of bricks after 7 days of curing

Table 10. Average density (±standard deviation)

Mixtures	Density (g/cm³)	Δ (%)
Soil-cement	1.81±0.05	-
E-0.125	1.55±0.05	-15
P-1.00	1.71±0.01	-5
EPS + polyethylene fibers	1.59±0.05	-12

Note: Δ (%) is the variation in density in relation to the reference mixture (soil-cement)

The average density of blocks with EPS residue and polyethylene fibers is presented in Figure 17 and Table 10, in comparison to the density of reference blocks (soil-cement), blocks with the optimal content of EPS (E-0.125), and blocks with the optimal content of polyethylene fibers (P-1.00).

It is evident that expanded polystyrene did contribute to the reduction of block density. The combination of both residues resulted in a block that is more resistant and 12% lighter than the reference blocks (soil-cement). When comparing the density of blocks solely with the incorporation of polyethylene fibers to the density of blocks containing both residues, the effect of EPS incorporation is still noticeable, leading to a reduction in density of approximately 7%.

4. Conclusions

The incorporation of expanded polystyrene residue was carried out with the aim of reducing the weight of adobe bricks, which was indeed achieved. However, this incorporation resulted in an 85% loss of compressive strength for the mixture containing 0.50% incorporation of this residue, along with cracks in the shrinkage test. On the other hand, the incorporation of polyethylene fibers was primarily aimed at containing the cracking of the soil-cement matrix in the shrinkage test. The incorporation of these fibers, at the studied levels, not only restrained the shrinkage of the soil-cement mixture but also provided an increase in compressive strength.

From a normative perspective, the mixtures E-0.125, E-0.25, and E-0.50, for a curing period of 7 days, do not meet the compressive strength criterion of equal to or greater than 1.5 MPa, as specified by NBR 16814 (ABNT, 2020). Despite the other mixtures meeting this criterion, it is emphasized that the method for evaluating compressive strength outlined in the Brazilian standard is different from what was used in the development of this study.

The results of the tests with the soil-cement adobe bricks incorporating EPS residue and reinforced with polyethylene fibers were satisfactory in terms of compressive strength and shrinkage. The brick produced with the simultaneous incorporation of residues, besides being lighter, showed an average compressive strength 59% higher than the reference soil-cement block, and it did not exhibit cracks or fissures in the shrinkage test.

ACKNOWLEDGEMENTS

For all the provided support, the authors thanks the Federal University of Mato Grosso (UFMT).

REFERENCES

[1] Associação Brasileira das Empresas de Limpeza Pública e Resíduos Especiais. Panorama dos resíduos sólidos no Brasil 2022. Accessed 27 December 2023. https://abrelpe.org.br/download-panorama-2022/.

[2] Ogunmakinde, O. E., Egbelakin, T., Sher, W., 2022, Contributions of the circular economy to the UN sustainable development goals through sustainable construction. Resources, Conservation & Recycling, 178. https://doi.org/10.1016/j.resconrec.2021.106023.

[3] Lizárraga-Mendiola, L., López-León, L. D., Vázquez Rodríguez, G. A., 2022, Municipal solid waste as a substitute for virgin materials in the construction industry: a review. Sustainability, 14. https://doi.org/10.3390/su142416343.

[4] Schützenhofer, S. et al., 2022, Improvement of environmental sustainability and circular economy through construction waste management for material reuse. Sustainability, 14. https://doi.org/10.3390/su141711087.

[5] Marvila, M. et al., 2022, Recycled Aggregate: a viable solution for sustainable concrete production. Materials, 15. https://doi.org/10.3390/ma15155276.

[6] Yuan, Q. et al., 2022, Utilisation of waste-to-energy fly ash in ceramic tiles. Construction and Building Materials, 347. https://doi.org/10.1016/j.conbuildmat.2022.128475.

[7] Yaro, N. S. A. et al., 2023, A comprehensive overview of the utilization of recycled waste materials and technologies in asphalt pavements: towards environmental and sustainable low-carbon roads. Processes, 11. https://doi.org/10.3390/pr11072095.

[8] Martins, J., and Ribeiro, M., 2021, O consumismo como fator preponderante para o aumento da geração de resíduos sólidos e os impactos ambientais na saúde pública. Revista de Direito Econômico e Socioambiental, 12(1), 123-152. https://doi.org/10.7213/rev.dir.econ.soc.v12i1.27478.

[9] Ahsan, M. U., Nasir, M., Abbas, J., 2020, Examining the causes of plastic bags usages and public perception about its effects on the natural environment. International Journal of Academic Research in Business and Social Sciences, 10(10), 80-96. https://dx.doi.org/10.6007/IJARBSS/v10-i10/7919.

[10] Compromisso Empresarial para Reciclagem. Ciclosoft. 2023. Accessed 27 December 2023. https://cempre.org.br/pesquisa-ciclosoft/.

[11] Redko, V. et al., 2024, Environmental impacts of 5-year plastic waste deposition on municipal waste landfills: a follow-up study. Science of the Total Environment, 906. https://doi.org/10.1016/j.scitotenv.2023.167710.

[12] Toffano, A. L. M. S. Política e gestão de resíduos sólidos urbanos: desafios e possibilidades. Doctoral thesis, Pós-Graduação em Arquitetura e Urbanismo, Universidade Federal Fluminense, Niterói, Brazil, 2021.

[13] Vanapalli, K. R. et al., 2019, Emissions and environmental burdens associated with plastic solid waste management. Plastics to Energy, 313-342. https://doi.org/10.1016/B978-0-12-813140-4.00012-1.

[14] Schyns, Z. O. G., Shaver, M. P., 2021, Mechanical recycling of packaging plastics: a review. Macromolecular Rapid Communications, 42(3). https://doi.org/10.1002/marc.202000415.

[15] Garcia, J. M., Robertson, M. L., 2017, The future of plastics recycling: chemical advances are increasing the proportion of polymer waste that can be recycled. Science, 358(6365), 870-872. https://doi.org/10.1126/science.aaq0324.

[16] Sulong, N. H. R., Mustapa, S. A. S., Rashid, M. K. A., 2019, Application of expanded polystyrene (EPS) in buildings and constructions: a review. Journal of Applied Polymer Science, 136(20). https://doi.org/10.1002/app.47529.

[17] Lima, P. S. et al., 2018, Incorporation of expanded polystyrene (EPS) in concrete: perspective of developing a sustainable solution. ReOnFacema, 4(4), 1260-1264.

[18] Hummels, H., Argyrou, A., 2021, Planetary demands: redefining sustainable development and sustainable entrepreneurship. Journal of Cleaner Production. 278. https://doi.org/10.1016/j.jclepro.2020.123804.

[19] Ahmed Ali, K., Ahmad, M. I., Yusup, Y., 2020, Issues, impacts, and mitigations of carbon dioxide emissions in the building sector. Sustainability, 12. https://doi:10.3390/su12187427.

[20] Weber, E., Campos, R. F. F., Borga, T., 2017, Análise da eficiência do tijolo ecológico solo-cimento na construção civil. IGNIS, 6(2), 18-34. https://doi.org/10.29327/223085.6.2-2.

[21] Schweig, E. O. et al., 2018, Adobe soil-cement bricks reinforced with kraft paper fibers. International Journal of Materials Engineering, 8(5), 101-108. https://doi.org/10.5923/j.ijme.20180805.04.

[22] Santos, I. B. et al., 2018, Adobe soil-lime bricks reinforced with kraft paper fibers. International Journal of Materials Engineering, 8(5), 128-133. https://doi.org/10.5923/j.ijme.20180805.07.

[23] Barroso, K. O., Novato, F. G. C. A., Ferreira, R. T. L., 2023, Adobe soil-cement bricks with wood sawdust residue addition. Engineering and Science, 12(3). https://doi.org/10.18607/ES20231216186.

[24] Associação Brasileira de Normas Técnicas. NBR 16814: Adobe – requisitos e métodos de ensaio. Rio de Janeiro, 2020. 26 p.

[25] Chen, L., and Lin, Z., 2021, Polyethylene: properties, production and applications. 3rd International Academic Exchange Conference on Science and Technology Innovation, Guangzhou, China, 1191-1196. https://doi.org/10.1109/IAECST54258.2021.9695646.

[26] Carvalho, C. H. R., Motta, L. A. C., 2019, Study about concrete with recycled expanded polystyrene. Revista IBRACON de Estruturas e Materiais, 12(6), 1390-1407. https://doi.org/10.1590/S1983-41952019000600010.

[27] Prasittisopin, L., Termkhajornkit, P., Kim, Y. H., 2022, Review of concrete with expanded polystyrene (EPS): performance and environmental aspects. Journal of Cleaner Production, 366. https://doi.org/10.1016/j.jclepro.2022.132919.

[28] Associação Brasileira de Normas Técnicas. NBR 16697: Cimento Portland - requisitos. Rio de Janeiro, 2018. 12 p.

[29] Associação Brasileira de Cimento Portland. Dosagem das misturas de solo-cimento: normas de dosagem e métodos de ensaio. São Paulo, 2004.

[30] Rotondaro, R. Adobe In: Neves, C., Faria, O. B (Org.). Técnicas de construção com terra. Bauru, São Paulo, Brasil: FEB-UNESP/PROTERRA, 2011. 16-25. Accessed 27 December 2023. http://www.redproterra.org.

[31] Buson, M. A. Kraftterra: desenvolvimento e análise preliminar do desempenho técnico de componentes de terra com a incorporação de fibras de papel kraft provenientes da reciclagem de sacos de cimento para vedação vertical. Doctoral thesis, Pós-Graduação em Arquitetura e Urbanismo, Universidade de Brasília, Brasilia, Brazil, 2009.

[32] Silva, B. A. Estudo de misturas solo cimento agregado reciclado de telhas cerâmicas para fabricação de blocos para alvenaria. Master thesis, Pós Graduação em Engenharia Civil, Universidade Federal de Uberlândia, Uberlândia, Brazil, 2015. https://doi.org/10.14393/ufu.di.2015.250.

[33] Burbano-Garcia, C. et al., 2022, Adobe mixtures reinforced with fibrillated polypropylene fibers: physical/mechanical/fracture/durability performance and its limits due to fiber clustering. Construction and Building Materials, 343. https://doi.org/10.1016/j.conbuildmat.2022.128102.

[34] Kafodya, I., Okonta, F., Kloukinas, P., 2019, Role of fiber inclusion in adobe masonry construction. Journal of Building Engineering, 26. https://doi.org/10.1016/j.jobe.2019.100904.

[35] Novato, F. G. C. A. Tijolos de adobe de solo-cimento com adição de resíduo de recapagem de pneus. Bachelor thesis, Graduação em Engenharia Civil, Universidade Federal do Mato Grosso, Barra do Garças, Brazil, 2019.