Soil-Cement Bricks Development Using Polymeric Waste

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Research Article

Keywords: Composites, Ecological brick, Reinforcement materials, Thermal insulation, Tire, Polyethylene Terephthalate

Posted Date: May 5th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-451591/v1

Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on November 8th, 2021. See the published version at https://doi.org/10.1007/s11356-021-16769-z.

Abstract

This research aimed to evaluate the effect of adding different polymeric waste percentages and types on the physical, mechanical, thermal and durability properties of soil-cement bricks. Tire and PET (Polyethylene Terephthalate) waste were evaluated at 1.5 and 3.0% percentages. The soil was characterized in terms of shrinkage, compaction, consistency limits, particle size and chemical analyses, whereas the waste particles were submitted to morphological characterization. The bricks were produced in an automatic press with a 90: 10 (m/m) soil: cement ratio. The soil-cement bricks were characterized by density, moisture, water absorption, loss of mass by immersion, compressive strength, thermal conductivity and microstructural analysis. PET waste stood out for its use as reinforcement in soil-cement bricks. The best performance was obtained for bricks reinforced with 1.5% PET, which showed a significant compressive strength improvement, meeting the marketing standards criteria, even after the durability test, as well as obtaining the lowest thermal conductivity values. The percentage increase from 1.5% to 3.0% fostered a significant water absorption and loss of mass increase, as well as a significant compressive strength reduction of the bricks.

1. Introduction

Soil-using construction is one of the oldest and most widely used techniques around the world. Soil-using constructions have been present since mankind felt the need to build a shelter instead of using only those provided by nature (Soares et al. 1996; Ferreira and Freire 2003; Touré et al. 2017; Sekhar and Nayak 2018; Saidi et al. 2018). At present, the need for environmental preservation and the tendency to natural resources shortage force construction industry to devise new concepts and technical solutions aiming at the sustainability of its activities, using a range of effective solutions, combined with known bio-construction techniques, which may be incorporated to human housing reality (Lai et al. 2019; Barbosa et al. 2019).

In this way, research development for the use of waste on the construction industry has been gaining relevance, aiming at lower energy demand and creating possibilities in housing advancements by reducing the use of non-renewable materials and construction materials cost. Soil-cement bricks are a sustainable alternative since there is low energy consumption in the soil extraction, not requiring the burning process, and, in some cases, not needing transportation as the bricks may be produced using the soil from the actual building site (Pecoriello and Barros 2004; Muntohar 2011; Barbosa et al. 2019). According to data from the Brazilian Micro and Small businesses support service - SEBRAE (2017), soil-cement bricks provide a 20 to 40% saving compared to conventional bricks. Barbosa et al. (2019), Saidi et al. (2018), Reddy and Latha (2014) and Muntohar (2011) also mentioned advantages such as similar compressive strength and improved thermal insulation for soil-cement bricks compared to conventional ones.

Soil-cement brick is obtained by the homogeneous mixture of soil, cement and water, in appropriate proportions, which, after compaction and wet curing, delivers a product with durability and adequate mechanical resistance (Motta et al. 2014; Saidi et al. 2018; Dantas et al. 2019; Barbosa et al. 2019; Barros et al. 2020; Reis et al. 2020). Cement is used as a soil stabilizer, allowing better interaction between materials and resulting in improved physical and mechanical properties. In this context, various studies mention the bricks stabilization using natural or synthetic particles, which results in a more resistant and more ductile composite material, which cannot avoid crack formation but controls their propagation (Montardo et al. 2001; Specht et al. 2002; Wang and He 2003; Malaiškiene et al. 2011; Zhang 2013; Cristelo et al. 2015; Laborel-Préneron et al. 2016; Naidu and Kona 2018; Arunraj et al. 2019).

Several types of materials may be used as soil-cement brick reinforcement, including waste. Among urban solid waste, plastics such as Polyethylene Terephthalate (PET) and tire have shown significant growth in the amount discarded, in line with the populations' economic development (Song et al. 2015; Alani et al. 2019). Both materials take up a lot of space in landfills, and if discarded incorrectly, it may cause major environmental and urban problems such as flooding in large urban centers and also serving as breeding grounds for diseases such as dengue, zika and chikungunya, especially in less economically developed countries.

Recycled PET is already used in the construction industry for water tanks, pipes and connections, taps, swimming pools, roof tiles, synthetic marble, paints and varnishes (ABIPET 2017). Also, some studies using PET as concrete aggregate (Capanema et al. 2014), mortar preparation (Reis and Carneiro 2012), and recycled PET added to concrete blocks without structural function (Modro et al. 2009; Barreto et al. 2019) have shown good results. Research using tire particles in building materials also showed potential, with studies on paving (Li et al. 2019), concrete blocks (Thakur et al. 2020), soil stabilization (Bekhiti et al. 2019), pavers (Altoé 2017; Fioriti et al. 2017) and cement-based panels (Vilela et al. 2017).

PET and tire waste use as reinforcement in soil-cement bricks may allow the correct use and added value for such materials, as well as bricks properties improvement, reducing production costs and augmenting the production chain sustainability. Despite the studies using PET and tires found in the literature show their potential for use (Sadek and El-Attar 2015; Paschoalin Filho et al. 2016), a better understanding of their use as reinforcement materials on the physical, mechanical, thermal and durability properties of bricks is needed. Also, a clearer definition of the most appropriate reinforcement material, as well as an understanding of the best material-reinforcement concentration combination is required. In this context, this research aimed to evaluate the effect of adding different percentages of PET and tire waste on the physical, mechanical, thermal and durability properties of soil-cement bricks.

2. Material And Methods

2.1 Raw materials

The soil was collected in the municipality of Lavras, Minas Gerais State, Brazil (21°14'7" S, 44°58'21" O), and went through a screening process to eliminate materials that could interfere on the molding. NBR 10833 standard (ABNT 2013) establishes that 100% of the soil must pass through the 4.75 mm sieve (#

4) and 10% to 50% through the 0.075 mm sieve (# 200) to be suitable for soil-cement bricks production. The cement used was CPII-E-32 (ASTM 2020).

Tire and Polyethylene terephthalate – PET waste were used for bricks production. Tire waste was obtained from Bkerp Reformadora de Pneus, a tire retreading company located in the municipality of Lavras, Minas Gerais state, Brazil. The PET was obtained by grinding soda bottles supplied by the Lavras Recyclable Material Collectors Association - ACAMAR, located in the municipality of Lavras, Minas Gerais state, Brazil. The PET particles were processed in a hammer mill for size homogenization. The PET and tire particles were classified by screening. The materials used for fiber cement production were the particles that passed through the 0.64 mm sieve and were retained in the 0.25 mm sieve.

2.2 Soil and particles characterization

Shrinkage testing was performed on the soil according to Research and Development Center (CEPED 1984) to verify the presence of expansive clays in the soil composition that might compromise the performance of the material due to shrinkage during drying. The soil sample was moistened until it obtained a plastic-consistency material, similar to an embossment mortar plaster and then placed inside a 60.0 cm long, 8.5 cm wide and 3.5 cm thick box. After the manual thickening, the material was left in the shade for seven days. After that, the box length retraction was measured and the added readings should be less than 20 mm and the sample should not present any transverse slit in the central part of the sample after seven days.

To obtain the optimum moisture and maximum dry specific weight values, the Normal Proctor type compaction tests were performed as per NBR 7182 (ABNT 2020) and NBR 12023 (ABNT 2012) standards. The two physical indexes obtained in this test, optimum moisture and maximum dry apparent specific weight, are relevant in studies with soils as they provide better working conditions and maximum compaction of the material allowing greater density, resistance and durability values.

To determine the consistency limits, the procedures described by NBR 6459 (ABNT 2017) and NBR 7180 standards (ABNT 2016) were followed. The Brazilian Portland Cement Association (ABCP 1986) and NBR 10833 standard (ABNT 2013) recommend the liquid limit be lower than 45% and the plasticity index be lower than 18%. Equation 1 was used for the plasticity index.

$$PI = LL - PL \quad (1)$$

Where

PI = plasticity index;

LL = liquid limit, corresponding to NBR 6459 standard (ABNT 2017);

PL = plasticity limit, corresponding to NBR 7180 (ABNT 2016).

The test for soil grain size determination was carried out according to the Soil Analysis Methods Manual (EMBRAPA 1997).

For PET and tire particles, the morphological characterization was done using Image J software. 30 readings to obtain the width and 30 for length were taken for each particle. Subsequently, the slenderness index, the particle length and width ratio were calculated. Both PET and tire had their density determined according to ASTM D1895 standard (ASTM 2017).

2.3 Bricks production

The treatments described in Table 1 were used to obtain the soil-cement bricks. The components were weighed and mixed in a planetary mixer to obtain a homogeneous mortar. Afterward, water was added and a new homogenization was performed and the mixture was transferred to an automatic press for bricks shaping. The amount of water used for each treatment was based on the optimum moisture obtained in the Normal Proctor compaction test. Soil-cement-particle bricks production followed the Technical report #112 (ABCP 1989) and Technical Study #35 (ABCP 1986) from ABCP – Brazilian Portland Cement Association. Specimens were molded with 20 x 9.5 x 5 cm (length, width and thickness) dimensions. The soil-cement-particle bricks production stages are seen in Figure 1.

After their production, the soil-cement bricks were placed on a flat floor in the shade and a covered and protected place as per ABCP (1986) guidelines. The bricks were submitted to daily wetting cycles for 7 consecutive days.

Table 1 – Treatments used for soil-cement bricks production

Reinforcement material	Reinforcement percentage (%)	Cement (%)	Soil (%)
No reinforcement	-	10	90
PET	1.5 and 3.0*	10	90
Tire			

* In relation to bricks` total weight.

2.4 Soil-cement-particle bricks characterization

Soil-cement-particle bricks characterization was performed after the 28-day curing period. For the physical characterization, density and moisture were determined as per NBR 8492 standard (ABNT 2012). The bricks were oven-dried until reaching a total loss of moisture. Then, after 24 hours, the bricks were weighed to obtain the dry weight. After that, they were immersed in water for 24 hours to obtain the wet weight. Water absorption and moisture quantification were performed as per Equations 2 and 3, respectively.

$$A = \frac{M2 - M1}{M1} X\,100 \quad (2)$$

Where

A= water absorption (%);

M1= oven-dried brick weight (g);

M2= saturated brick weight (g).

$$U = \frac{(Mtf - Ms)}{Ms} X\,100 \quad (3)$$

Where

U= moisture (%);

Mtf= newly-produced-brick weight (g);

Ms= dry brick weight (g).

Loss of mass by immersion determination was performed as per ME-61 standard (SECRETARIA DE SERVIÇOS PÚBLICOS 2003). After curing, the bricks were sent to the oven until achieving a mortar constancy. After that, the bricks were placed in an immersion container and the water was slowly added until its blade reached a minimum 1 cm above the outer face of the brick. Equation 4 was used to determine the loss of mass by immersion.

$$Pi = \frac{Md\ X\ 100}{Mo} X\,100 \quad (4)$$

Where

Pi= loss of mass by immersion (%);

Md= dry ground weight (detached part of the specimen) (g);

Mo= soil dry weight (g).

The compressive strength test on the bricks was performed on an Arotec universal testing machine (TimeShijin, WDW-20E model) equipped with a 200 kN load cell. The test was carried out as per the NBR 8492 standard (ABNT 2012).

To determine soil-cement bricks thermal conductivity, a module with heat actuator was used at the bottom keeping the temperature at 45ºC and sensors to read the temperature that passes through the brick. 1°C/min was the heating rate and 3h and 30 minutes was the test cycle for each treatment. Data were collected during this period by sensors from the Data Collector equipment, IM DC 100-01E model. The test provided the temperature values at the base of the standard (heating system) and the lower and upper surfaces of the brick. The thermal conductivity was obtained using Equation 5, as per NBR 15220-2 standard (ABNT 2008).

$$\lambda = P.\ E / \Delta T \quad (5)$$

Where

λ- Thermal conductivity [W/m°C];

P – Radiation by area measurement [W/m²];

E – Specimen thickness [m];

ΔT - Temperature variation between the specimens faces [°C].

The durability test was performed based on the accelerated aging method, as per NBR 13554 standard (ABNT 2012), which classifies the soil-cement durability by wetting and drying procedures. Six wetting and drying cycles were performed. The immersion time in the water was 5h and the oven time was 42h at 71±2°C for each cycle. After aging, the density, water absorption, loss of mass and compressive strength of bricks were analyzed once more.

Microscopy was performed using the Stereo Microscope with Epi-fluorescence SMZ 1500 (Nikon) to evaluate the influence of the reinforcement materials and soil-cement bricks matrix interaction.

For the physical, mechanical and thermal properties analysis, a completely randomized design was used, in a 2 x 2-factor scheme (two types of reinforcement materials - PET and tire combined with two percentages of reinforcement - 1.5 and 3.0%), as well as a control treatment not added with reinforcement materials. The Dunnett's test was performed for the treatments compared to the control at a 5% significance level. To evaluate the interaction between the type of reinforcement and its percentage, analysis of variance and Scott-Knott means test were performed, both at 5% significance. The data obtained were compared with the marketing standard for simple compression and water absorption NBR 8492 (ABNT 2012) and loss of mass by immersion (SECRETARIA DE SERVIÇOS PÚBLICOS 2003).

3. Results And Discussion

3.1 Morphological characterization of particles

PET and tire particles morphological characterization is shown in Table 2. PET particles presented the highest average values for length and width, differing statistically from the tire particles. The slenderness index, characterized as the particle`s length and width ratio, was higher for tire particles and statistically different from PET particles. The slenderness index may directly affect physical and mechanical properties as it influences the particle-matrix contact area. According to Silva et al. (2014), the larger the contact area the more efficient the particle adherence to the matrix, fostering better dimensional stability, as well as composites with improved mechanical properties.

The PET particles had the highest average density value, differing statistically from tire particles. Ge et al. (2015) obtained 1.35 g/cm³ and 0.44 g/cm^3 average density values for PET and tire particles, respectively (Bekhiti et al. 2019).

Table 2 –PET and tire particles morphological and physical characterisation

Particle	Density (g/cm³)	Length (mm)	Width (mm)	Slenderness Index
PET	1.38 $^{(0,05)}$ A	0.57 $^{(0,09)}$ A	0.20 $^{(0,06)}$ A	3.14 $^{(0,87)}$ B
Tire	0.56 $^{(0,04)}$ B	0.30 $^{(0,06)}$ B	0.05 $^{(0,01)}$ B	6.42 $^{(1,73)}$ A

Averages followed by the same letter in the column did not differ statistically from each other by the Scott-Knott test at a 5% significance level. Standard deviation shown in brackets.

3.2 Soil characterization

The soil collected met the characteristics set by NBR 10833 standard (ABNT 2013) - 100% soil passing through the 4.75 mm (# 4) and 38% passing through the 0.075 mm (n° 200) sieve. The soil contained 56% of sand, categorizing it as sandy soil, suitable for soil-cement bricks production. According to the Brazilian Portland Cement Association (ABCP 1985), soil containing 50% to 90% of sand produces more durable soil-cement bricks. For Souza et al. (2008), they are the most suitable ones for soil-cement bricks production as they provide appropriate strength values with low cement consumption.

For soil shrinkage, an 8.64 mm average value was obtained. According to guidelines set by (CEPED 1984), the shrinkage sum at the soil ends should be lower than 20 mm, making its use feasible for soil-cement bricks production.

For consistency limits from the collected soil, 30.63% liquid limit, 20.73% plasticity limit and 9.90% plasticity index average values were obtained, as per ABCP (1986) and NBR 10833 standards (ABNT 2013), which establish the maximum 45% and 18% values for liquid limit and plasticity index, respectively.

Table 3 and Figure 2 show the maximum dry specific weight ($\gamma_{dmáx}$) and optimal moisture (w_{ot}) average values obtained from the Normal Proctor type compaction test for each evaluated treatment. The $\gamma_{dmáx}$ values increased with the addition of the particles when compared with the control treatment.

It was also noted that the average values for treatments added with 1.5% waste were higher than for those added with 3.0%. Despite the use of polymeric waste fosters better geometric composition with the materials resulting in greater mixture compaction (Zak et al. 2016; Gupta et al. 2020), compaction was impaired in treatments with a higher waste percentage, increasing the voids and decreasing $\gamma_{dmáx}$ (Ferreira and Oliveira 2007; Tran et al. 2018; Mishra and Kumar Gupta 2018; Bekhiti et al. 2019).

Milani and Freire (2006) state that compaction improves material properties since material compression occurs by mechanical energy. Thus, soil compaction increases density and strength, as well as reducing voids and decreasing permeability and contraction.

It was also observed that tire particles allowed greater homogeneity in the compaction curve variation as a function of moisture, with well-defined maximum compaction peaks for each percentage, also observed for the control treatment (Figure 2). Whereas PET particles presented greater variation to obtain the optimal compaction point obtaining some maximum compaction stabilization with the moisture increase. This may be due to their hydrophobic characteristic combined with the low surface roughness, which affects their interaction with the soil-cement mixture, impairing the maximum compaction rate determination.

Overall, the values obtained for optimal moisture increased by adding particles when compared to the control treatment. This result is linked to the need for larger amounts of water for treatments with lower percentages to obtain greater compaction and better internal accommodation of particles (Hidalgo et al. 2019; Bekhiti et al. 2019).

Table 3 – Optimal moisture and maximum γd values

Treatment	Maximum γd (g/cm³)	Optimal moisture (%)
PET 1.5%	1.329	16.13
PET 3.0%	1.281	13.50
Tire 1.5%	1.356	17.58
Tire 3.0%	1.314	16.82
Control	1.236	15.08

Table 4 shows the soil grain size analysis with the clay, silt and sand percentages. According to the AASHTO (American Association of State Highway and Transportation Officials) soil classification, the soil used in this study was classified as Type A-4, which justifies the 9: 1 soil: cement ratio in weight, as recommended by the ABCP (1985). For clay + silt content, the soil presented 44%, a value below 50%, which is the maximum particle size distribution value so that the soils may be stabilized with cement in an economically viable manner (HRB 1961). For Segantini and Wada (2011), soils with clay + silt content lower than 20%, do not present an initial compaction resistance. According to Milani and Freire (2006), enough amounts of fine grains (clay + silt) may confer greater plasticity to the mixture directly affecting the properties of the bricks.

The soil used in this study had 56% sand content. According to Murmu and Patel (2018) and Rahman et al. (2016), soils that present sand contents higher than 50% produce soil-cement bricks with greater durability and adequate physical and mechanical properties. On the other hand, clayey soils present higher cement expenditure and more difficult mortar spraying and stabilizing due to low sand percentage (Yadav and Tiwari 2017; Sekhar and Nayak 2018).

Table 4 – Soil grain size analysis

Components / References	Clay (%)	Silt (%)	Sand (%)	Clay + silt (%)
Soil	42	2	56	44
ICPA (1973)	5 - 10	10 - 20	-	-
MAC (1975)	20 – 30	< 30	40 - 70	-
CEPED (1984)	< 20	-	45 - 90	10 – 55
PCA (1969)	-	-	-	10 – 35
CINVA (1963)	-	-	45 - 80	20 – 25

*ICPA: Instituto del Cemento Portland Argentino; *MAC: Ministere des Affaires Culturalles; *CEPED: Centro de Investigación y Desarrollo; *PCA: Portland Cement Association; *CINVA: Centro Interamericano de Vivienda y Planificación.

3.3 Soil-cement bricks characterization

3.3.1 Physical Characterization

Table 5 shows the compaction degree and moisture average values of soil-cement bricks for each treatment after production. Compaction degree reduction on bricks was noted for all treatments with reinforcement due to the reinforcement-matrix interaction, greater generation of voids and compaction difficulty of these materials due to their volume, elastic characteristics and dispersion by the matrix (Zak et al. 2016; Yadav and Tiwari 2017).

Despite the different compaction degrees of treatments, only the treatment with 3.0% tire particles met the ideal range proposed by (Bueno and Vilar 1980), which determines the compaction degree to range from 95 to 105%. The other treatments had compaction degrees higher than the defined range due to the high compaction created by automatic pressing equipment.

For bricks moisture, only the treatment with 3.0% tire differed statistically from the control treatment. It presented the highest average value since the tire presents high elastic modulus, which, after compaction, tends to return to its natural state causing the distancing of components from the matrix, generating pores and affecting water/moisture absorption, as stated by Vilela et al. (2018). Also, such treatment presented the lowest compaction rate.

Table 5 – Soil-cement bricks compaction and moisture average values

Treatments	Compaction degree (CD)	Moisture (%)
PET 1.5%	112.85 (1,26) *	12.49 (0,43) ns
PET 3.0%	112.89 (1,27) *	12.80 (2,26) ns
Tire 1.5%	110.55 (0,54) *	13.76 (1,17) ns
Tire 3.0%	104.12 (0,40) *	17.96 (0,68) *
Control	119.90 (1,56)	13.02 (2,92)

*Differentiated statistically by the Dunnett test (α = 0.05) from the control treatment; ns did not differ statistically by the Dunnett test (α = 0.05) from the control treatment. Standard deviation values shown in brackets.

Interaction between the type of material (PET and tire) and the percentage of particle used (1.5 and 3.0%) was noted only for bricks moisture, as shown in Table 6. It was noted that the lowest moisture values were obtained using higher tire particles concentrations. This is related to the higher tire particles return rate after pressure removal during production, generating greater porosity in the bricks' matrix, as seen in Figure 2D, causing a lower compaction degree (Table 5) and higher moisture absorption by the bricks components.

Table 6 – Average moisture values for bricks as a function of reinforcement material percentage and type

Type of material	**Percentage (%)**	
	1.5	**3.0**
PET	12.49 (0,43) aA	12.80 (2,26) aA
Tire	13.76 (1,17) aA	17.96 (0,68) bB

*Averages followed by the same letter did not show any statistical difference by Scott-Knott test at a 5% significance level. Lower case letters refer to the values of the columns, uppercase letters refer to the values of the rows. Standard deviation values shown in brackets.

Table 7 shows the average density values, before and after the accelerated aging test for soil-cement bricks for each treatment. It was observed that only the treatments added with 3.0% PET and tire particles at 28 curing days and the treatment with 3.0% tire particles after accelerated aging showed significant density reduction when compared to the control treatment. Such result was due to the higher volume of particles added to soil-cement brick, which caused □$_{dmáx}$ reduction (Table 5), as well as to a higher return rate to tire particles compression, increasing the number of pores in both cases (Figure 2C and 2D).

Table 7 - Average density values of soil-cement bricks before and after accelerated aging

Treatments	**Density at 28 days (g/cm³)**	**Density after aging**
PET 1.5%	1.500 (0,017) ns	1.486 (0,001) ns
PET 3.0%	1.446 (0,016) *	1.434 (0,008) ns
Tire 1.5%	1.499 (0,007) ns	1.445 (0,022) ns
Tire 3.0%	1.368 (0,005) *	1.328 (0,004) *
Control	1.482 (0,019)	1.461 (0,043)

*Differentiated statistically by the Dunnett test (α = 0.05) from the control treatment; ns did not differ statistically by the Dunnett test (α = 0.05) from the control treatment. Standard deviation values shown in brackets.

The interaction was observed between the type of material (PET and tire) and the percentage of particle used (1.5 and 3.0%) for density, before and after the aging test, as shown in Table 8. A significant effect of the type of reinforcement material occurred only for the 3.0% percentage at 28 curing days and for the 1.5 and 3.0% ones after accelerated aging. The bricks added with tire showed the lowest density in all cases, which is due to the high tire particles return rate after bricks pressing release (Vilela et al. 2018) resulting in a higher amount of pores when compared to the bricks added with PET (Figure 2), as well as to tire density lower than PET (Table 2), which increases the number of particles needed to compose a pre-established reinforcement mass, thus decreasing reinforcement-matrix interaction. Salih et al. (2020) and Bekhiti et al. (2019) also noted the reinforcement material density effect on the final density of bricks.

Table 8 – Bricks density average values, before and after the durability test as a function of reinforcement material percentage and type

Type of material	Density at 28 days		After aging	
	Percentage (%)			
	1.5	3.0	1.5	3.0
PET	1.500 (0,017) aA	1.446 (0,016) aB	1.486 (0,001) aA	1.434 (0,008) aB
Tire	1.499 (0,007) aA	1.368 (0,005) bB	1.445 (0,022) bA	1.328 (0,004) bB

*Averages followed by the same letter did not show any statistical difference by Scott-Knott test at 5% significance level. Lower case letters refer to the values of the columns and uppercase letters refer to the values of the rows. Standard deviation values shown in brackets.

Bricks added with 1.5% tire did not present any density differentiation from PET at 28 curing days due to the lower amount of reinforcement material used and the higher matrix resistance before accelerated aging. After the wetting and drying process, the matrix starts cracking, which reduces its resistance (Huzaifah et al. 2019; Manohar et al. 2019). It allows a higher return rate of compressed tire particles and consequently increasing the pores, even more, thus reducing the density.

When evaluating the type of material on each percentage, a decrease in the density values with the increase in the reinforcement material addition was noted. This reduction was observed for both types of reinforcement material and the bricks analyzed at 28 curing days and after accelerated aging. The increase in the number of particles directly increases the number of pores (Zak et al. 2016; Salih et al. 2020). According to Milani and Freire (2006), higher pore concentration results in the low interaction between the soil-cement system and waste, causing negative effects on physical and mechanical properties.

Table 9 shows the average water absorption values obtained for soil-cement bricks on each treatment, before and after accelerated aging. It may be noticed that the water absorption after the durability test followed the same pattern as before the wetting and drying cycles. Only the 3.0% tire reinforcement material caused a significant bricks water absorption increase. Therefore, it is directly linked to the density (Table 8) and porosity (Figure 2D) of the bricks.

Despite not absorbing water, the tire had an average value higher than the control treatment. This is due to the tire particles return after pressure removal during production, which generated pores, allowing a lower compaction degree (Table 5) and, consequently, a higher water penetration (Vilela et al. 2018; Garcia et al. 2018; Elenien et al. 2018).

Table 9 - Soil-cement bricks average water absorption values before and after accelerated aging

Treatments	Water absorption at 28 days (%)	Water absorption after aging (%)
PET 1.5%	21.06 $^{(0,22)}$ ns	21.07 $^{(0,53)}$ ns
PET 3.0%	22.57 $^{(0,52)}$ ns	23.17 $^{(0,04)}$ ns
Tire 1.5%	21.93 $^{(1,05)}$ ns	22.36 $^{(0,10)}$ ns
Tire 3.0%	27.13 $^{(0,39)}$ *	27.43 $^{(0,42)}$ *
Control	22.62 $^{(0,33)}$	22.16 $^{(1,00)}$

*Differentiated statistically by the Dunnett test (α = 0.05) from the control treatment; ns did not differ statistically by the Dunnett test (α = 0.05) from the control treatment. Standard deviation values shown in brackets.

Interaction between the type of material used (PET and tire) and the particle percentage (1.5 and 3.0%) occurred for water absorption, before and after the durability test, as shown in Table 10. The effect of reinforcement material type was only verified in the 3.0% percentage, both at 28 days and after accelerated aging. In both conditions, the bricks added with PET presented the lowest water absorption values. Such values are linked to the higher compaction degree of bricks (Table 5), lower porosity (Figure 2) and higher density (Table 8). According to Jin et al. (2018), the low optimal moisture value may reduce the pore size, hindering water penetration, hence reducing absorption.

For the effect of percentages on each reinforcement material, it was observed for both materials (PET and tire) and the two analysis conditions (28 days and aged) that higher reinforcement material concentrations generate higher water absorption, which is linked to lower matrix densification (Table 2) and higher pores generation (Figure 2) facilitating water penetrating the bricks.

Table 10 - Water absorption average values before and after durability test as a function of reinforcement material type and percentage

Water absorption at 28 days		After aging	
Percentage (%)			
1.5	3.0	1.5	3.0
21.06 $^{(0,22)}$ aB	22.57 $^{(0,52)}$ bA	21.07 $^{(0,53)}$ aB	23.17 $^{(0,04)}$ bA
21.93 $^{(1,05)}$ aB	27.13 $^{(0,39)}$ aA	22.36 $^{(0,10)}$ aB	27.43 $^{(0,42)}$ aA

*Averages followed by the same letter did not show any statistical difference by Scott-Knott test at 5% significance level. Lower case letters refer to the values of the columns and uppercase letters to the values of the rows. Standard deviation values shown in brackets.

The evaluated treatments reached average values higher than the 20% maximum value for water absorption set by NBR 10834 (ABNT 2013) standard and ABCP (1989). The high clay content presented by the soil (Table 4) may have contributed to the average values for treatments being higher than recommended since clayey soils tend to retain more water due to their macro and microstructural aspects (Fredlund and Anqing Xing 1994; Murmu and Patel 2018).

Table 11 shows the average loss of mass values by immersion of soil-cement bricks, before and after the accelerated aging test. It was verified at 28 curing days that only the bricks added with 3.0% tire differed from the control treatment, obtaining the highest loss of mass value. This confirms the expansion of the brick with higher tire percentages after production and consequently the adhesion loss between matrix-reinforcement (Yadav and Tiwari 2017; Elenien et al. 2018).

After the durability test, it was observed that the treatments with 3.0% reinforcement differed statistically from the control, showing an increase in loss of mass values. Such an increase is linked to the generation of cracks in the bricks' matrix after wetting and drying cycles. It may either be only superficial, as well as be the result of adhesion loss between matrix-reinforcement and also between the matrix components (Bekhiti et al. 2019; Salih et al. 2020), which also resulted in bricks lower density values for such treatments (Table 8).

Table 11 - Loss of mass by immersion average values for soil-cement bricks before and after accelerated aging

Treatments	Loss of mass by immersion at 28 days (%)	Loss of mass by immersion after accelerated aging (%)
PET 1.5%	1.39 $^{(0,34)}$ ns	5.89 $^{(3,50)}$ ns
PET 3.0%	1.13 $^{(0,21)}$ ns	15.27 $^{(5,37)}$ *
Tire 1.5%	0.82 $^{(0,13)}$ ns	5.63 $^{(2,19)}$ ns
Tire 3.0%	2.05 $^{(0,94)}$ *	23.47 $^{(7,57)}$ *
Control	0.78 $^{(0,12)}$	3.45 $^{(1,59)}$

*Differentiated statistically by the Dunnett test (α = 0.05) from the control treatment; ns did not differ statistically by the Dunnett test (α = 0.05) from the control treatment. Standard deviation values shown in brackets.

For loss of mass by immersion, before and after accelerated aging, the interaction between the type of material (PET and tire) and the particle percentage (1.5 and 3.0%) occurred, as shown in Table 12. A significant effect of type of material was observed on bricks only at 28 curing days. PET at 1.5% presented the highest loss of mass value, whereas the opposite occurred at 3.0% with the lowest loss of mass value obtained for bricks added with PET. This may be due to the highest slenderness index (Table

2) presented by tire particles, which aids the reinforcement-matrix interaction at lower concentrations, avoiding loss of mass to a larger extent (Boukour and Benmalek 2016; Salih et al. 2020). However, at higher concentrations, the bricks had a lower compaction degree (Table 5) due to tire particles return rate, fostering higher porosity values (Figure 2) and greater adhesion loss with the matrix, which increased bricks` loss of mass.

Table 12 - Loss of mass by immersion average values, before and after the durability test, as per reinforcement material type and percentage

Type of material	Loss of mass at 28 days		After aging	
	Percentage (%)			
	1.5	3.0	1.5	3.0
PET	1.39 $^{(0,34)}$ aA	1.13 $^{(0,21)}$ bA	5.89 $^{(3,50)}$ aB	15.27 $^{(5,37)}$ aA
Tire	0.82 $^{(0,13)}$ bB	2.05 $^{(0,94)}$ aA	5.63 $^{(2,19)}$ aB	23.47 $^{(7,57)}$ aA

*Averages followed by the same letter did not show any statistical difference by Scott-Knott test at 5% significance. Lower case letters refer to the values of the columns and uppercase letters refer to the values of the rows. Standard deviation values shown in brackets.

When analyzing the type of material on each percentage, reinforcement concentration effect did not occur only for PET before accelerated aging. For other comparisons, before and after aging, the higher percentage of reinforcement increased loss of mass values due to lower compaction and density values and higher porosity values of composite (Jin et al. 2018; Hidalgo et al. 2019; Salih et al. 2020).

3.3.2 Mechanical characterization

Soil-cement bricks compressive strength values, before and after the aging test, are shown in Table 13. The treatments presented distinct behavior before and after the accelerated aging test. Before aging, treatments with 1.5% PET and 3.0% tire showed some statistical difference when compared to the control. The treatment added with PET showed the highest resistance value, while the treatment added with 3.0% tire showed a considerable strength value drop. After the durability test, all treatments statistically differed from the control treatment, especially the treatments added with 1.5% and 3.0% PET that showed the highest strength values, while the treatments added with tire had strength values lower than the control treatment.

The highest compressive strength values for bricks added with 1.5% PET before aging and for bricks added with 1.5 and 3.0% PET after aging are linked to an adequate reinforcement-matrix interaction (Figure 2), increasing bricks strength due to crack bridging effect by PET particles (Wang et al. 2017; Sappakittipakorn et al. 2018). On the other hand, the lower compressive strength for treatments added with 3.0% tire at 28 curing days and for both tire percentages after accelerated aging is linked to the lower bricks compaction degree (Table 5), lower density (Table 7), and higher porosity (Figure 2). According to Piani et al. (2020); Hidalgo et al. (2019) and Piani et al. (2018), porosity significantly affects the composites' compressive strength.

Table 13 - Compressive strength average values for soil-cement bricks before and after accelerated aging

Treatments	Compressive strength at 28 days (MPa)	Compressive strength after accelerated aging (MPa)
PET 1.5%	2.00 $^{(0,17)}$ *	2.16 $^{(0,03)}$ *
PET 3.0%	1.65 $^{(0,25)}$ ns	2.08 $^{(0,05)}$ *
Tire 1.5%	1.35 $^{(0,07)}$ ns	1.43 $^{(0,02)}$ *
Tire 3.0%	1.00 $^{(0,07)}$ *	0.85 $^{(0,00)}$ *
Control	1.42 $^{(0,35)}$	1.74 $^{(0,02)}$

*Differentiated statistically by the Dunnett test (α = 0.05) from the control treatment; ns did not differ statistically by the Dunnett test (α = 0.05) from the control treatment. Standard deviation values shown in brackets.

The bricks showed increased compressive strength after accelerated aging, except for the treatment added with 3.0% tire. For Milani and Freire (2006), this increase in strength shows the effect of soil stabilization with the mixture, which is linked to cement continued hydration during the wetting and drying cycles at accelerated aging (Taylor 1998; Teixeira et al. 2020). Despite generating surface cracks in the matrix resulting in greater loss of mass (Table 11), it may have improved the reinforcement-matrix interaction increasing the mechanical resistance of bricks added with PET.

Despite the statistical differentiation compared to the control treatment after accelerated aging, the bricks added with 1.5% tire also increased mechanical resistance by 5.93% when compared to the values obtained at 28 curing days. However, the increase was lower than that observed for the control treatment, which was 22.54%. Such a result is due to the lower matrix-tire particle interaction caused by the characteristic return rate to compression (Vilela et al. 2018). Also, the higher the concentration used the lower the interaction, which reduced compressive strength of bricks added with 3.0% tire by 15% when the bricks used in the durability test were compared to the ones at 28 curing days.

For compressive strength before and after the durability test, the interaction between type of material (PET and tire) and the percentage of particles used (1.5 and 3.0%) was observed, shown in Table 14. When evaluating the 1.5% and 3.0% percentages of particles on each type of material, the treatment with PET presented the highest average compressive strength value, before and after the accelerated aging test due to the lower amount of pores (Figure 2), higher compaction and density degrees (Table 5 and 7) compared to bricks added with tire.

When analyzing the effect of percentage on each type of material, only the concentration effect on bricks added with PET after aging was not noticed. For bricks added with PET at 28 curing days and for bricks added with tire at 28 curing days and after accelerated aging, the increase in the number of particles decreased the compressive strength values. The higher concentration of particles in the brick matrix decreases density and increases porosity, which is a determining factor for the compressive strength decrease of bricks (Jin et al. 2018; Hidalgo et al. 2019; Piani et al. 2020).

Table 14 - Average compressive strength values before and after the durability test, as per reinforcement material type and percentage

Types of material	Compressive strength at 28 days		After aging	
	Percentage (%)			
	1.5	3.0	1.5	3.0
PET	2.00 $^{(0,17)}$ aA	1.65 $^{(0,25)}$ aB	2.16 $^{(0,03)}$ aA	2.08 $^{(0,05)}$ aA
Tire	1.35 $^{(0,07)}$ bA	1.00 $^{(0,07)}$ bB	1.43 $^{(0,02)}$ bA	0.85 $^{(0,00)}$ bB

*Averages followed by the same letter did not show any statistical difference by Scott-Knott test at 5% significance. Lower case letters refer to the values of the columns, uppercase letters refer to the values of the rows. Standard deviation values shown in brackets.

Only the treatment added with 1.5% PET before the durability test and the treatments added with 1.5% and 3.0% PET after accelerated aging, met the ABCP (1989) and NBR 10834 standards (ABCP 2013), which set 2.0 MPa as the minimum compressive strength value and also IS 1725 standard (IS 1982) that establishes 1.96 MPa as the minimum strength for class 20. The high amount of clay found in the soil (Table 4) is a determining factor that may have influenced the low compressive strength of most treatments, including the control one.

3.3.3 Soil-cement bricks heat insulation

Table 15 shows the average thermal conductivity values for soil-cement bricks as well as the variations on treatments average values compared to the control. For thermal conductivity, no interaction occurred between the type of reinforcement material and the percentage of particles. It was observed that all treatments added with reinforcement reduced the thermal conductivity values, however, only the bricks produced with 1.5% PET and 3.0% tire showed any significant thermal conductivity values reduction when compared to control treatment ones.

The thermal conductivity values reduction on treatments is due to the higher amount of pores observed in such treatments (Figure 2) compared to other percentages evaluated on each type of reinforcement material since air pockets offer better insulation in composites (Kazmierczak et al. 2020), and also the low thermal conductivity values for PET (0.24 W / m.°C) and tire (0.15 W / m.K) (Speight 2005).

Table 15 – Soil-cement bricks average thermal conductivity values

Treatments	Thermal conductivity (W/m°C)	Δ
PET 1.5%	1.814 $^{(0,005)}$ *	-11.94
PET 3.0%	1.909 $^{(0,028)}$ ns	-7.33
Tire 1.5%	1.881 $^{(0,046)}$ ns	-8.69
Tire 3.0%	1.851 $^{(0,184)}$ *	-10.15
Control	2.060 $^{(0,031)}$	

*Differentiated statistically by the Dunnett test (α = 0.05) from the control treatment; ns did not differ statistically by the Dunnett test (α = 0.05) from the control treatment. Standard deviation values shown in brackets.

Overall, such treatments show the effectiveness of reinforcement materials as heat sinks since the particles acted as obstacles and also generated pores that helped reduce thermal conductivity, which is excellent for use in the construction industry. It reduces indoor air conditioning energy consumption, lowering costs and increasing the sustainable characteristics of a construction (Khedari et al. 2005; Turgut and Gumuscu 2013; Ashour et al. 2015).

4. Conclusion

PET waste stood out for its use as reinforcement in soil-cement bricks. When analyzing the physical, mechanical and thermal properties of bricks, the best result was obtained for bricks reinforced with 1.5% PET that showed a significant compressive strength improvement, meeting marketing standards criteria even after the durability test, as well as obtaining the lowest thermal conductivity values.

For bricks, the increase in concentration from 1.5% to 3.0% increased significantly water absorption and loss of mass and significantly reduced compressive strength.

The use of tire particles as reinforcement material in soil-cement bricks is not recommended since this material is affected by the return rate after its compaction, increasing matrix porosity, and negatively impairing the physical and mechanical properties of the bricks.

Declarations

ACKNOWLEDGEMENTS

The authors would like to thank the Minas Gerais State Agency for Research and Development (FAPEMIG - APQ-02204-16), the National Council of Technological and Scientific Development (CNPq - Grants

305214/2017-9; Grants 305662/2020-1) and the Coordination for the Improvement of Higher Education Personnel (CAPES) for their financial support.

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Figures

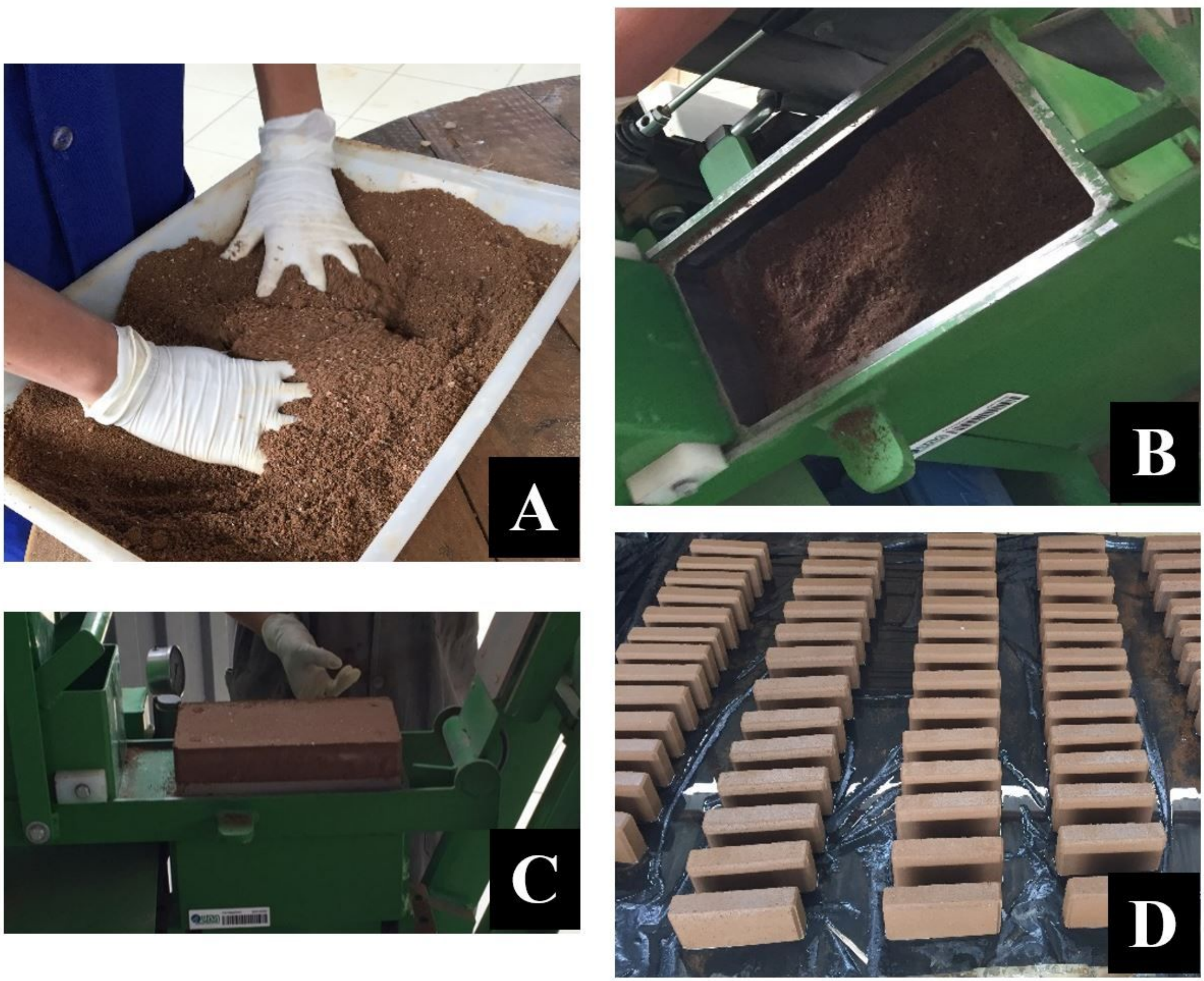

Figure 1

Soil-cement-particle bricks production stages. A) Homogenized raw materials; B) Mixture lodging in the press; C) Compressed bricks; D) Bricks during the curing process

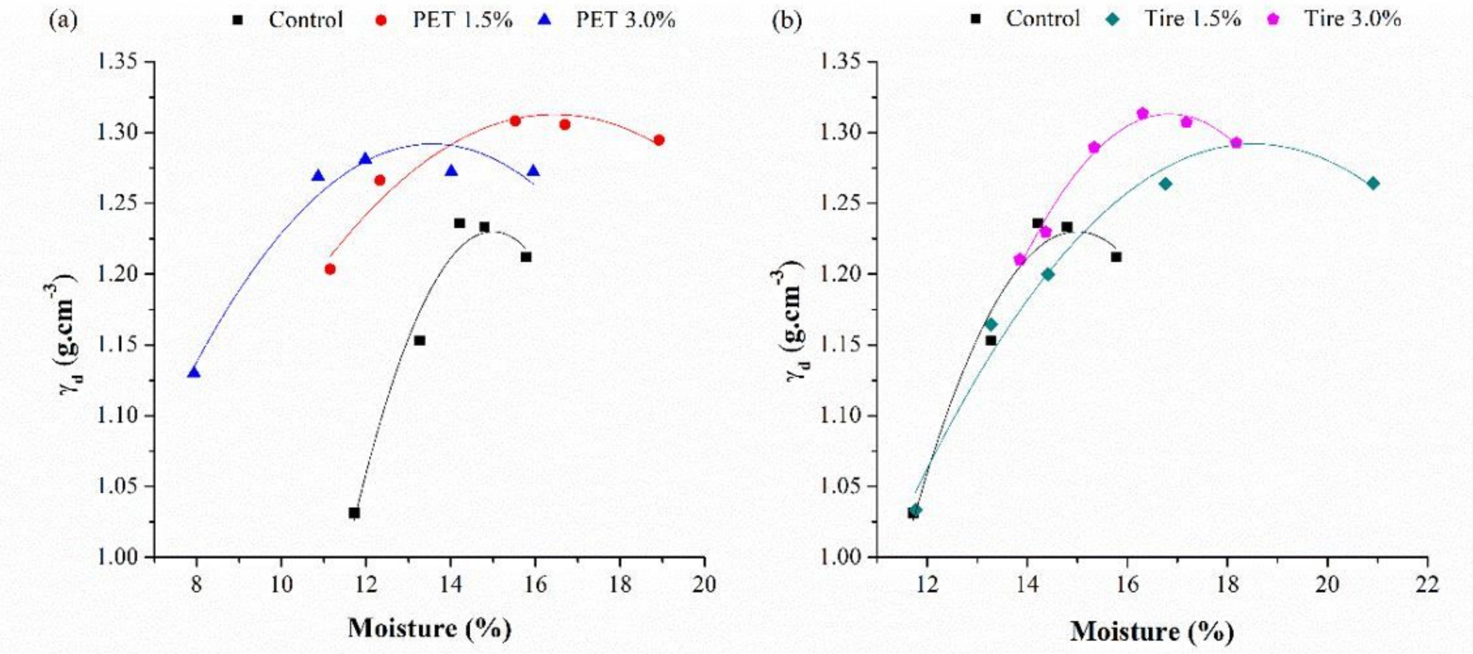

Figure 2

Compaction curves as a function of reinforcement materials percentages and types

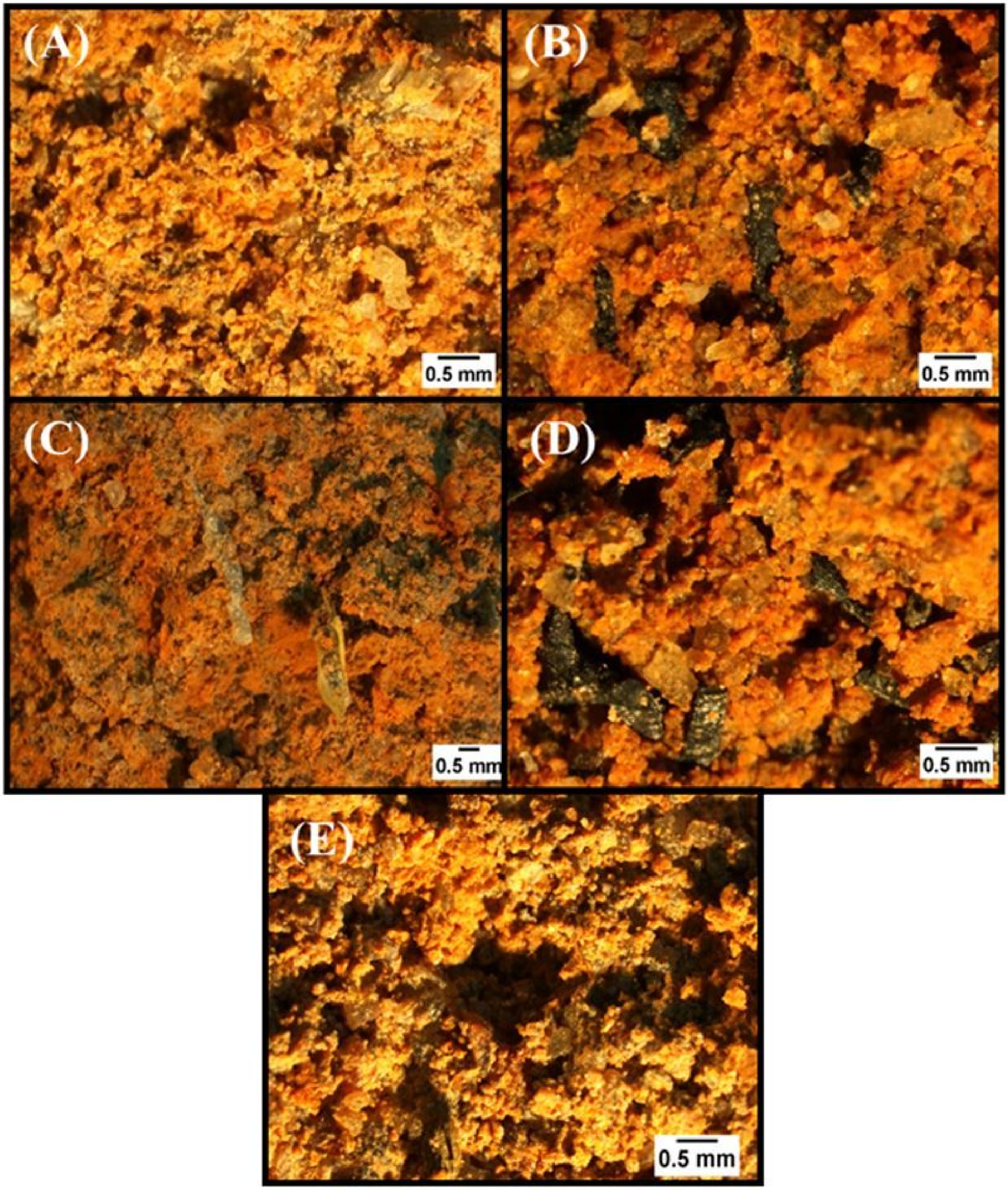

Figure 3

Soil-cement bricks microstructural analysis. A) 1.5% PET; B) 1.5% Tire; C) 3.0% PET; D) 3.0% Tire and E) Control