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# LIGNOCELLULOSIC MATERIALS AS SOIL-CEMENT BRICKS REINFORCEMENT

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## Abstract

The need for environmental preservation requires civil engineering to reach new concepts and technical solutions aiming at the sustainability of its activities and products. In this context, this study aimed to evaluate the effect of using different types and percentages of vegetable particles on the physical, mechanical and thermal properties of soil-cement bricks. Bamboo, rice husk and coffee husk particles at 1.5 and 3% percentages and a control treatment not using the particle were evaluated. The chemical properties, shrinkage, compaction, consistency limits and grain size were characterized for the soil; and the anatomical, chemical and physical properties for the lignocellulosic particles. The bricks were produced using an automatic press and characterized after the curing process for density, water absorption, porosity, loss of mass by immersion, compressive strength, durability and thermal conductivity. The increase in the lignocellulosic waste percentage caused a mechanical strength decrease and bricks` porosity and water absorption increase. However, it caused a decrease in density and an enhancement in loss of mass and thermal insulation properties. The bricks produced with rice husk obtained the best results in terms of mechanical and thermal properties, and were still among the best treatments for physical properties, standing out among the lignocellulosic waste as an alternative raw material source for soil-cement bricks production.

**Keywords:** Composites; ecological brick; vegetable waste; thermal comfort; durability; physical and mechanical properties.

## Declarations

- *Ethics approval and consent to participate* - Not applicable.
- *Consent for publication* - Not applicable.
- *Availability of data and materials* - All data generated or analysed during this study are included in this published article.
- *Competing interests* - The authors declare that they have no competing interests.

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- *Authors' contributions:*

*TPFS* - Conceptualization; Investigation; Methodology; Writing – review & editing
*NPFC* – Investigation; Methodology; Writing – review & editing.
*NCA* – Investigation; Methodology; Writing – review & editing.
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QSV - Investigation; Methodology
*JFM* – Investigation; Methodology; Writing – review & editing.
*RFM* - Conceptualization; Funding acquisition;Investigation; Methodology; Resources; Supervision; Writing – review & editing.
*All authors read and approved the final manuscript.*

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## 1. INTRODUCTION

Solid waste disposal is a current problem worldwide since most of them are discarded onto open dumps, wastelands, rivers, seas, and elsewhere, creating a hazard to health and the environment. Such waste could be an alternative source of raw material for the building sector, thus shifting the industrial production paradigm to a closed production model, where the waste is recycled and incorporated into the production process (Wang et al. 2019; Benachio et al. 2020).

The civil engineering industry stands out within the sectors of the economy and one of its main challenges is to combine sustainable development and profitability due to the large consumption of non-renewable materials and the generation of large amounts of rubble and used material waste (Rahimi and Ghezavati 2018; Lai et al. 2019). Therefore, the search for more sustainable materials that require less energy for their production, use natural raw materials and ensure economic, social and ecological advance is of major interest (Siddique et al. 2018; Zuccarello et al. 2018; Ciampa et al. 2020).

Among the construction techniques and materials presenting low environmental impact, the soil-cement brick deserves special attention due to its ecological character, as it does not require the burning process, unlike traditional construction systems, avoiding harmful gases being released to the environment, as well as using soil as the main raw material, which is abundantly found in nature having great potential for waste incorporation in its matrix to gain strength and improve its properties (Khedari et al. 2005; Turgut and Gumuscu 2013; Tao et al. 2018; Barros et al. 2020a).

Lignocellulosic waste has been an excellent alternative due to the promising character of fibers in these materials, which may increase compressive strength due to better cracks interconnection, reduced density and improved thermal insulation (Kellersztein et al. 2019; Asim et al. 2020). These lignocellulosic materials might even be agro-industrial waste often illegally disposed of in the environment, causing environmental and sanitary problems (Torkaman et al. 2014; Bertolini et al. 2014; Kammoun and Trabelsi 2019).

Rice husk, coffee husk and bamboo have shown good results in the making of some composites, such as bricks, polyurethane foams, concrete and high-density polyethylene, which present as an advantage their high availability. For this reason, they have been the object of study to various researchers in different materials (Saleh et al. 2014; Huang et al. 2018; Wang et al. 2019; Ishak et al. 2019). The United States Department of Agriculture (USDA 2020) estimates 10.5 million tons of coffee production worldwide for 2020/21, generating around 5.25 million tons of coffee husk since a single ton of coffee beans generates approximately 50% of the coffee husk (Esquivel and Jiménez 2012). According to the Food and Agriculture Organization, the global rice production forecast for 2020 is 509.2 million tons (FAO 2020), 20% of which is rice husk (Pandey et al. 2000). On the other hand, bamboo is rapid-growing renewable biomass and widely available worldwide, facilitating its use for energy production, new materials, among other applications (Zhong et al. 2018; Gu et al. 2018; Sharma et al. 2018).

However, the difficulty for producing composites using lignocellulosic waste is due to the adhesion between the fibers/particle and the matrix, which directly influences the composite physical and mechanical properties. Therefore, the evaluation of the most appropriate type of lignocellulosic material, the ideal concentration of reinforcement and the effects of lignocellulosic materials chemical composition, geometric and physical properties on the bricks` properties are deemed necessary, which have so far been scarcely investigated (Zivkovic et al. 2016; Luz et al. 2018; Nascimento et al. 2018; Agüero et al. 2020).

In this context, this study aimed to evaluate the use of different types and percentages of lignocellulosic materials on the thermal, physical, mechanical, microstructural and durability properties of soil-cement bricks to determine the most appropriate production variables for new technological properties desirable for the bricks, as well as enabling their proper disposal and adding value to lignocellulosic waste.

## 2 MATERIALS AND METHODS

### 2.1 Raw materials

The soil used to produce bricks was collected in the municipality of Lavras, located in the southern region of Minas Gerais State, Brazil, at Longitude 21°14'12" and Latitude 44°58'26" geographical coordinates. The soil was sifted to eliminate undesirable and harmful materials as per NBR 10833 (31). The cement used was CPII-F, commonly used in the soil-cement bricks production (Silva et al. 2014; Garcia et al. 2018; Bekhiti et al. 2019). The bamboo (Bambusa vulgaris), rice husk and coffee husk particles were supplied by a bamboo toothpick, rice processing and coffee company, respectively, all located in the south of Minas Gerais State, Brazil.

### 2.2 Soil characterization

The soil shrinkage test was performed according to the procedures reported by the Research and Development Center (CEPED 1984) to check the presence of expansive clays in the soil composition since they impair the performance of the material due to shrinkage during drying. To obtain the values of optimum humidity and maximum specific dry weight, the compaction test was carried out by the Normal Proctor method, as per NBR 7182 (ABNT 2020) and NBR 12023 (ABNT 2012) standards. The consistency limits were established according to the procedures exposed in the NBR 6459 (ABNT 2017) and NBR 7180 (ABNT 2016) standards.

The soil grain size composition was determined by combining sedimentation and screening, as per procedures described in NBR 7181 (ABNT 2017b) and NBR NM ISO 3310-1 standards (ABNT 2010). Soil textural analysis was also performed, as per procedures reported by Gee and Bauder (Gee and Bauder 2018), determining the type of soil according to the Feret's diagram (Moran 1984). Chemical analyses were performed for pH (in water at a 1: 2.5 ratio) and organic matter determination as per the Brazilian Agricultural Research Corporation guidelines (EMBRAPA 1979).

### 2.3 Lignocellulosic particles characterization

Particles with grain size between 0.250 and 0.420mm were used for bricks production, as per França et al. (2018) and Vilela et al. (2020) guidelines. The samples morphological characterization was performed using ImageJ® (Powerful Image Analysis) software. For length, diameter and slenderness index of particles, 30 length and 30 width measurements were collected for each type of particle. The slenderness index was obtained using the length and diameter relation of particles.

For the chemical characterization, the samples were ground in a Willy-type rotor mill and classified in 40- and 60-mesh sieves. The particles retained in the 60-mesh sieve were used. The methodology based on NBR 14853 (ABNT 2010b) standard was used to obtain the total extractive content, NBR 7989 standard (ABNT 2010c) for lignin, NBR 13999 standard (ABNT 2017c) for ash content and the procedure reported by Kennedy et al. (1987) for cellulose. Holocellulose was obtained by difference, according to the equation: Holocellulose = 100-(Lignin + Total Extractives + Ashes) and hemicellulose was determined by the difference between holocellulose and cellulose amount.

For the particles, physical characterization, bulk density, basic density and water absorption were determined by the method by Azzini et al. (1981), by NBR 11941 standard (ABNT 2003) and by ASTM D 570 standard (ASTM 2018), respectively.

## 2.4 Soil-cement bricks production

The experimental design presented in Table 1 was used for the bricks production, evaluating different types of lignocellulosic materials and the percentage of particles replacing soil. For specimen production, the bricks components were weighed and mixed manually. Soon after, water was added for further homogenization, taking into account the optimum humidity obtained by the Normal Proctor test. The mixture was transferred to the automated press to obtain brick forms. The Technical Bulletin 111 (ABCP 2000) and Technical Study 35 (ABCP 1986) guidelines were followed for soil-cement-particle bricks production. The specimens were produced at 20 x 9.5 x 5 cm (length, width and thickness) dimensions.

**Table 1**- Evaluated treatments for soil-cement brick production

| Reinforcement material | % of reinforcement* | Cement (%) | Soil (%) |
|---|---|---|---|
| Without reinforcement | - | 7 | 93 |
| Rice husk | 1.5 and 3 | 7 | 91.5 and 90 |
| Coffee husk | 1.5 and 3 | 7 | 91.5 and 90 |
| Bamboo | 1,5 and 3 | 7 | 91.5 and 90 |

*% in dry weight

After their production, the soil-cement bricks were packed in a box at 98% humidity level and stored in a covered and protected place away from sunlight as recommended by the Brazilian Portland Cement Association (ABCP 1985). The bricks were wet twice daily for 7 days. After that, the bricks were removed from the wet room and placed in the shade and a covered and protected place for a 28-day curing process.

### 2.5 Soil-cement bricks characterization

Soil-cement bricks water absorption and bulk density properties characterization were obtained as per NBR 8492 (ABNT 2012b) standard guidelines. Apparent porosity was determined as per ASTM C20 (ASTM 2015). Loss of mass by absorption was established according to ME-61 (SSP 2003). For mechanical strength characterization, the bricks were submitted to the compressive strength test as per NBR 8492 (ABNT 2012b) standard guidelines.

Accelerated aging was performed to evaluate the bricks' behavior after prolonged exposure to adverse weather, as per NBR 13554 standard (ABNT 2012c) guidelines. The specimens were submitted to six wetting and drying cycles, each cycle corresponding to 5h in the water at room temperature and 42h in an oven at 71± 2ºC. After the six wetting and drying cycles, the bricks were evaluated for compressive strength, water absorption, porosity and loss of mass.

To determine the soil-cement bricks thermal insulation, a module with heat actuators at the bottom was used to maintain the temperature at 45ºC and sensors to read the temperatures placed at the top of the module, that is, the temperature that goes through the brick, in every module there were thermal insulating materials. The heating rate was 1°C/min and the test cycle for each treatment was 7 hours and 30 minutes. Afterward, the readings were sent to the computer for comparison and data storage. This test aimed to obtain the heat flow through the soil-cement brick from the heat transfer rate (q) from the brick's flat surface. The thermal conductivity was calculated using the formula described below, according to NBR 15220-2 standard specifications (ABNT 2005).

$$\lambda = (270 \, . \, e) \, \Delta T$$

λ= thermal conductivity (W/ (m. °C).
e= brick thickness (m)
ΔT= Panel temperature variation

For the microstructural characterization of soil-cement bricks, a matrix-particle interface evaluation, before and after aging, was carried out using a Nikon SMZ 1500 Stereo microscope with Epi-fluorescence.

### 2.6 Data analysis

For the analysis of the lignocellulosic materials and soil characterization data, an entirely randomized design was performed, with analysis of variance and Scott-Knott average test, both at a 5% significance level. For the bricks properties analysis, an entirely randomized design was used in a 3 x 2 factorial scheme (three types of lignocellulosic particles - rice husk, coffee husk and bamboo combined with two reinforcement percentages (1.5 and 3%), and a control treatment with no reinforcement materials. Dunnett's test, at a 5% significance level, was carried out to compare each treatment using lignocellulosic materials with the control treatment (without reinforcement). In the evaluation of the interaction between the factors particle type and reinforcement percentage, as well as in the evaluation of each factor separately, when no interaction was observed, analysis of variance and Scott-Knott average test were performed, both at a 5% significance level.

The data were compared with the trading standard for simple compression NBR 8492 (ABNT 2012b) and IS 1725 (IS 1982), water absorption NBR 8492 (ABNT 2012d) and loss of mass by immersion ME-61 (SSP 2003).

# 3 RESULTS AND DISCUSSION

## 3.1 Lignocellulosic particles characterization

Table 2 shows the waste average length and width and the average slenderness index values. No statistical difference was noted for the waste particles length. However, for width, the coffee husk and bamboo differed from the rice husk, presenting the lowest values. For the slenderness index, there were differences in all waste, where bamboo had the highest index, followed by rice husk and coffee husk, respectively. The slenderness index might affect the particle-matrix contact area, since the larger this contact area, the better the particle adherence to the matrix and the greater the composite dimensional stability resulting in composites with better mechanical properties (Silva et al. 2014; Cabral et al. 2017).

**Table 2** – Lignocellulosic waste morphological characterization

| Treatment | Length | Width | Slenderness index |
|---|---|---|---|
| **Rice husk** | 1.99 $^{(0,69)}$ A | 0.87 $^{(0,13)}$ A | 2.35 $^{(0,86)}$ B |
| **Coffee husk** | 1.84 $^{(0,80)}$ A | 0.77 $^{(0,17)}$ B | 1.38 $^{(1,17)}$ C |
| **Bamboo** | 2.21 $^{(1,06)}$ A | 0.70 $^{(0,14)}$ B | 3.11 $^{(1,12)}$ A |

Averages followed by the same letter in the column did not differ from each other by the Scott-Knott test at a 5% significance level. Values in brackets correspond to the standard deviation.

Table 3 shows the lignocellulosic waste chemical components average values. For extractives, all the waste were differentiated from each other. The smallest amounts of extractives were found for rice husk, followed by bamboo and coffee husk, respectively. Large amounts of extractives may affect the cement curing and consequently impair the waste particles-cement matrix interaction (Almeida et al. 2013; Diquélou et al. 2016).

**Table 3** – Lignocellulosic waste chemical characterization

| Treatment | Extractives | Lignin | Cellulose | Hemicellulose | Ashes |
|---|---|---|---|---|---|
| | | | % | | |
| **Rice husk** | 8.36 $^{(0.51)}$ C | 27.90 $^{(1.05)}$ A | 21.95 $^{(0,77)}$ C | 34.13 $^{(0,58)}$ A | 9.60 $^{(0,91)}$ A |
| **Coffee husk** | 30.50 $^{(0.31)}$ A | 20.58 $^{(0.4)}$ B | 26.30 $^{(0,45)}$ B | 22.51 $^{(0,45)}$ B | 7.42 $^{(0,27)}$ B |
| **Bamboo** | 9.95 $^{(0.43)}$ B | 27.70 $^{(0.5)}$ A | 37.18 $^{(0,63)}$ A | 26.70 $^{(0,48)}$ B | 3.70 $^{(0,01)}$ C |

Averages followed by the same letter in the column did not differ from each other by the Scott-Knott test at a 5% significance level. Values in brackets correspond to the standard deviation.

For lignin, the rice husk and bamboo were statistically similar, as opposed to coffee husk which had the smallest lignin amount. Higher lignin amount is desirable since it is an incrusting substance that works as an adhesive between the lignocellulosic materials tissues and consequently increases the mechanical strength of composites, as well as protecting particles from eventual degradation (Vanholme et al. 2012; Dababi et al. 2016).

For cellulose, all the waste differed from each other and the highest values were found for bamboo, coffee husk and rice husk, respectively. High cellulose amounts may be beneficial since they provide composites with excellent mechanical properties (Wei and Meyer 2015; Cheng et al. 2018). For hemicellulose, the coffee husk and bamboo were statistically similar and differentiated from rice husk, which had the highest average value. According to Frybort et al. (2008), hemicellulose is an inhibiting substance that delays the adhesion of the particles to cement, preventing the proper formation of composite, as well as being one of the most water-absorbing chemical components; hence high hemicellulose amounts may be harmful. For ashes, which reflect the materials` inorganic components, all the waste differed from each other, and the rice husk had the highest amount, followed by coffee husk and bamboo, respectively.

The values for basic density, bulk density and maximum absorption of waste are seen in Table 4. For basic density and bulk density, all waste differed statistically and coffee husk showed the lowest density, followed by bamboo and rice husk, respectively. The low lignocellulosic particles density and particle bundles formation may decrease the final density of composites and improve thermal insulation properties since it provides greater matrix porosity (Zak et al. 2016; Aminudin et al. 2017).

**Table 4** – Lignocellulosic waste physical characterization

| Waste | Basic density ($g.cm^{-3}$) | Bulk density (%) | Water absorption (%) |
|---|---|---|---|
| **Rice husk** | 0.368 $^{(0,01)}$ A | 0.395 $^{(0,04)}$ A | 279 $^{(15,42)}$ A |
| **Coffee husk** | 0.154 $^{(0,02)}$ C | 0.170 $^{(0,05)}$ C | 374 $^{(3,76)}$ B |
| **Bamboo** | 0.250 $^{(0,01)}$ B | 0.272 $^{(0,04)}$ B | 414 $^{(4,06)}$ C |

Averages followed by the same letter in the column did not differ from each other by the Scott-Knott test at a 5% significance level. Values in brackets correspond to the standard deviation.

For water absorption, all waste differed from each other and bamboo had the highest absorption values, followed by coffee husk and rice husk, respectively. Although the rice husk has a greater hemicellulose amount, a hydrophilic chemical compound, the particles water absorption was small, which could be linked to a greater ash amount found in rice husk, indicating the presence of a protective wax involving the particles, making them absorb less water (Javed et al. 2015; Olupot et al. 2016). The high water absorption of lignocellulosic materials is a substantial obstacle, as it may cause particles to swell, affecting the physical and mechanical properties of composites (Pasquini et al. 2006; Madurwar et al. 2013).

### 3.2 Soil characterization

The soil used presented 65% sand, within the 60 to 80% ideal range (Ker et al. 2015; Acchar and Marques 2016; Jordan et al. 2019; Barbosa et al. 2019) for soil-cement bricks production, classified as sandy-clay soil according to Feret's diagram (Moran 1984). For grain size test, most grains found in the soil presented grain sizes ranging from 0,42mm to 2mm with the grain sizes ranging from 2mm to 4,8mm was found in smaller amounts. For the 4,8mm mesh sieve, the soil had a 100% passage. The lignocellulosic particles used with the soil presented grain sizes ranging between 0.250 and 0.420mm.

Table 5 presents the optimal moisture (OM) and the maximum specific dry weight (γd) found in the compaction test, as well as the liquidity limit (LL), plasticity limit (PL) and plasticity index (PI) values of soils for each treatment.

**Table 5** - Average values for optimum moisture and maximum specific dry weight and consistency limits.

| Treatment | OM (%) | $\gamma_d$ (g.cm$^{-3}$) | LL (%) | PL (%) | PI (%) |
|---|---|---|---|---|---|
| **Soil** | 20.59 | 1.87 | 37.59 $^{(1,20)}$ | 26.84 $^{(0,82)}$ | 10.75 $^{(0,33)}$ |
| **Soil + 1.5% Rice husk** | 20.60 | 1.84 | 35.66 $^{(0,57)}$ | 28.75 $^{(0,42)}$ | 6.91 $^{(0,48)}$ |
| **Soil + 3% Rice husk** | 21.26 | 1.86 | 37.49 $^{(0,37)}$ | 27.43 $^{(1,35)}$ | 10.06 $^{(0,19)}$ |
| **Soil + 1.5% Coffee husk** | 19.70 | 1.88 | 38.61 $^{(0,79)}$ | 30.52 $^{(0,49)}$ | 8.15 $^{(0,53)}$ |
| **Soil + 3% Coffee husk** | 19.96 | 1.83 | 40.91 $^{(0,46)}$ | 28.42 $^{(0,59)}$ | 9.01 $^{(0,36)}$ |
| **Soil + 1.5% Bamboo** | 21.08 | 1.82 | 38.67 $^{(0,75)}$ | 27.19 $^{(1,20)}$ | 11.42 $^{(1,12)}$ |
| **Soil + 3% Bamboo** | 21.29 | 1.84 | 37.43 $^{(1,9)}$ | 28.26 $^{(0,84)}$ | 12.65 $^{(0,80)}$ |

Values in brackets correspond to the standard deviation.

For the optimal moistures obtained during the compaction test, the treatments with 3% reinforcement presented higher values than the treatments with 1.5%. Such humidity increase occurs due to lignocellulosic particles hygroscopic capacity (Hablot et al. 2013). The specific weight found decreased by adding lignocellulosic particles, except for the treatment with 1.5% coffee husk. This was due to the lignocellulosic particles low density (Table 4), the higher water absorption of such materials (Table 4) and their geometric characteristics (Table 2), which generates more pores, decreasing the compacted material's specific dry weight (Kim and Lee 2011; Danso and Manu 2020).

Miranda et al. (2011), evaluating the potential of grits in soil-cement brick production, also noted a tendency to increase the optimal moisture content and reduce the specific dry weight as the grits content increased. The authors linked the results to greater water absorption by the grit particles due to their higher porosity. Castro et al. (2019) evaluated the effects of coffee husk particles (Coffea arabica L.) incorporation in partial cement replacement on the physical, mechanical and thermal properties of soil-cement bricks and the results showed that greater husk content reduced the apparent specific dry weight, due to the lignocellulosic material low density.

The treatment added with 1.5% coffee husk presented a higher specific weight, even for the control treatment, due to its low slenderness index (Table 2), nearing a spherical shape and, thus easing the filling of the matrix pores (Giroudon et al. 2019; Danso and Manu 2020). It was also noted that for treatments with rice and coffee husks, which had higher slenderness indexes, the specific weight increased with the increase of reinforcement concentration, justified by filling the voids by insertion of reinforcement material with higher slenderness indexes and in smaller concentrations.

The soil plasticity index, when comparing the soils added with 1.5% and 3% lignocellulosic particles, increased with greater waste percentage, indicating that the soil may maintain its plastic state even with a greater variation in moisture. For all soils, liquidity limits (LL) and plasticity indexes (PI) met the ABCP specifications (ABCP 1986), which sets an LL and a PI lower than 45% and 18%, respectively. The liquidity limit, plasticity limit and grain size obtained classified the soil as A2, according to HRB (Highway Research Board), hence, setting the ideal cement amount to be used at 7%, as per ABCP (ABCP 1986). Table 6 presents the shrinkage values for soil (control) and soil added with particles for soil-cement bricks production. It was noted that all treatments differed from the control one, presenting smaller shrinkage. The soil (control) presented a 23 mm shrinkage, higher than the 20 mm limit recommended by Research and Development Center (CEPED 1984). A crack was also noted in the center of the specimen (control). The test was repeated and even so, the crack in the center occurred. The soil added with waste did not present any cracks in the central part and their retractions varied from 17 to 20 mm, set as ideal by Research and Development Center (CEPED 1984). Therefore, the shrinkage was reduced in the soil added with waste, a significant result, since the linear shrinkage causes cracks, losing bearing capacity and affecting masonry quality (Bruxel et al. 2012).

**Table 6** – Soil Shrinkage (mm)

| **Soil** | **Soil + 1.5% RH** | **Soil + 3% RH** | **Soil + 1.5% CH** | **Soil + 3% CH** | **Soil + 1.5% Bamboo** | **Soil + 3% Bamboo** |
|---|---|---|---|---|---|---|
| 23 $^{(1,33)}$ B | 18 $^{(0,67)}$ A | 18 $^{(0,67)}$ A | 19 $^{(0,67)}$ A | 20 $^{(1,33)}$ A | 18 $^{(0,67)}$ A | 17 $^{(1,33)}$ A |

Averages followed by the same letter did not differ from each other by the Scott-Knott test, at a 5% significance level. Values in brackets correspond to the standard deviation.

The soil used for soil-cement bricks production had an acidic pH of 5.6. According to Ingles (Ingles 1968), acid soils are hard to stabilize with cement, and then neutral or basic pH soils are desirable. The soil used had a 0.15% organic matter, below the limit considered by Blucher (Blucher 1951), who states that the organic matter content in the soil should be low, setting the maximum safe limit at 2%. Organic matter affects soil-cement quality, causing mechanical strength to reach very low values, due to the presence of sugars and humic acid (Blucher 1951).

## 3.3 Soil-cement bricks characterization

### 3.3.1 Soil-cement bricks physical characterization

Table 7 shows the average bulk density values for each treatment, before and after accelerated aging, as well as the waste-produced-bricks average value variation compared to the control ones. For bulk density, no significant effect of reinforcement addition after 28 days of curing was observed. For aged bricks, the treatment with 3% coffee husk was the only one statistically different compared to the control treatment. This is due to the lower density of coffee husk (Table 4), requiring a greater number of particles to make a specific reinforcement mixture, resulting in less interaction with the matrix, greater particles interlacing, thus lower bricks density, when applied in greater volume (Abdul Khalil et al. 2012; Wei et al. 2018; Giroudon et al. 2019; Hamidon et al. 2019).

It is worth mentioning that density directly affects the composites\` properties since the higher the density the better its mechanical strength, however lower will be its thermal insulation capacity (Xie et al. 2016; Takai-Yamashita and Fuji 2020).

**Table 7** – Soil-cement-particle bricks bulk density

| Treatment | Bulk Density (g/cm³) | Δ (%) | Bulk Density (Aged) (g/cm³) | Δ (%) |
|---|---|---|---|---|
| **1.5% R.H.** | 1.56 $^{(0,10)}$ ns a | 6.71 | 1.48 $^{(0,01)}$ ns b | 2.78 |
| **3% R.H.** | 1.47 $^{(0,01)}$ ns a | -1.34 | 1.45 $^{(0,01)}$ ns a | 0.69 |
| **1.5% C.H.** | 1.52 $^{(0,01)}$ ns a | 2.01 | 1.47 $^{(0,01)}$ ns a | 2.08 |
| **3% C.H.** | 1.44 $^{(0,01)}$ ns a | -3.36 | 1.37 $^{(0,01)}$ * b | -4.86 |
| **1.5% B.** | 1.46 $^{(0,01)}$ ns a | -2.01 | 1.42 $^{(0,01)}$ ns b | -1.39 |
| **3% B.** | 1.41 $^{(0,01)}$ ns a | -5.37 | 1.39 $^{(0,01)}$ ns a | -3.47 |
| **Control** | 1.49 $^{(0,03)}$ a | | 1.44 $^{(0,05)}$ a | |

*Statistically differed from control treatment by Dunnett test (α=0.05); ns did not statistically differ from control treatment by Dunnett test (α=0.05). Averages followed by the same lower case letter in the line did not differ by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation. R.H. - Rice husk; C.H. - Coffee husk; and B - Bamboo.

The treatments with 1.5% rice husk, 3% coffee husk and 1.5% bamboo showed significant bulk density reduction after the aging cycles when comparing the bricks at 28 curing days and aged ones for each treatment. This result was due to particle-matrix adherence loss caused by degradation and dimensional movement during the aging cycles, which dislocated the particles forming pores, as seen in Figure 1, a more evident effect in these treatments due to their lower maximum compaction (Table 5). Farrapo et al. (2017), in the production of cement-based composites with cellulose fibers, also noted that the wetting and drying cycles generate partial cellulose adhesion loss to the cement matrix.

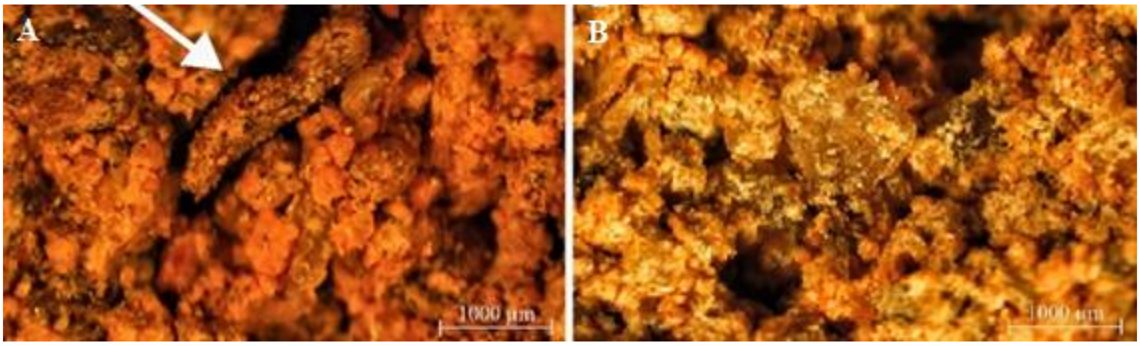


**Figure 1** - Optical microscopy image of aged and non-aged soil-cement bricks with 3% coffee husk. A) Coffee husk particle not adhered to the aged bricks matrix; B) Brick with coffee husk at 28 curing days.

For the bricks` bulk density at 28 curing days, no correlation was noted between the waste (rice husk, coffee husk and bamboo) and the two percentages (1.5% and 3%). Figure 2 shows the average bulk density values according to the type of waste and the reinforcement percentages. When the bulk density was evaluated as a function of waste, it was observed that the treatments with rice husk and coffee husk were statistically similar and different from the bamboo treatment, which presented a lower bulk density. This is due to the higher water absorption of bamboo particles (Table 4), generating greater swelling in the particles and thus more pores. Also, to a higher slenderness index (Table 2) that reduced the maximum dry specific weight when compared to the other treatments (Table 5), reducing the brick`s density.

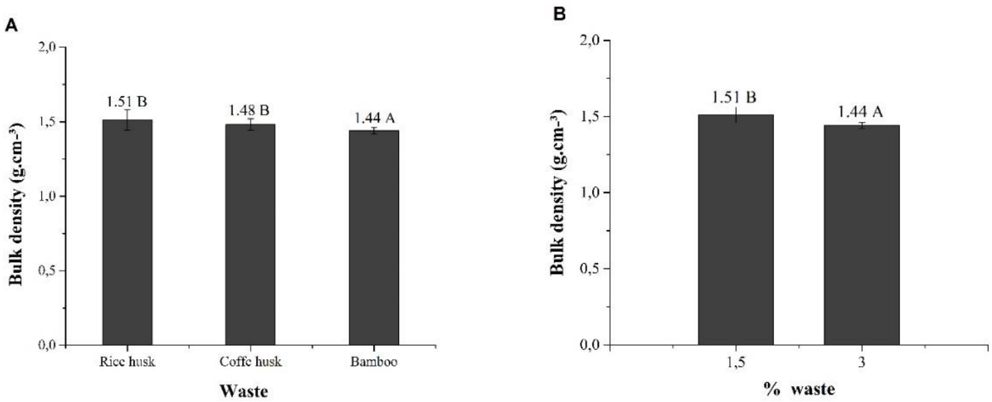


**Figure 2 -** Bulk density A) as a function of waste type, and B) as a function of waste percentage. Averages followed by the same letter did not differ from each other by the Scott-Knott test at a 5% significance level.

For bricks density evaluation as a function of waste percentage at 28 curing days, statistical difference between the two percentages was observed, where the highest bulk density values were obtained for the treatments with 1.5% reinforcement. This is linked to the lignocellulosic particles low-density since the higher the amount of waste, the lower the final density of the composite. Besides, some treatments require higher amounts of water contents to achieve the ideal brick shaping consistency, thus, the greater the amount of water, the greater the formation of pores (Bentchikou et al. 2012; Zak et al. 2016; Farrapo et al. 2017; Danso and Manu 2020).

Zak et al. (2016), when evaluating mixtures of soil, cement, gypsum, hemp and flax fibers, also observed a decrease in composite density by adding higher percentages of vegetable matter.

For the aged bricks, an interaction between the type of lignocellulosic material and percentages of reinforcement occurred. The results for bulk density are seen in Table 8. For the types of waste on each evaluated percentage, it was noted that both the 1.5% and 3% ones presented some statistical difference. For the 1.5% waste, the bricks added with bamboo differed from the others, presenting a lower bulk density. Despite the lower density of coffee husk particles compared to those of bamboo (Table 4), the bamboo particles showed the highest slenderness index values (Table 2) and their bricks presented the lowest maximum compaction values (Table 5), which provides a greater adherence loss between reinforcement and matrix during the aging cycles, generating pores and reducing density (Castro et al. 2017; Giroudon et al. 2019).

For the 3% percentage, all waste were differentiated among each other, with the bricks produced with rice husk presenting the highest average density, followed by the bricks with bamboo, and with coffee husk (lowest density). Thus, a direct correlation between the bricks density after aging and the treatments maximum compression degree was noted (Table 5).

**Table 8** – Aged soil-cement-particle bricks bulk density ($g.cm^{-3}$)

| Treatment | Rice husk | Coffee husk | Bamboo |
|---|---|---|---|
| **1.5%** | 1.48 $^{(0,01)}$ Bb | 1.47 $^{(0,01)}$ Bb | 1.42 $^{(0,01)}$ Ba |
| **3%** | 1.45 $^{(0,01)}$ Ac | 1.37 $^{(0,01)}$ Aa | 1.39 $^{(0,01)}$ Ab |

Averages followed by the same uppercase letter (in the column) and lower case (in the row) did not differ from each other by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation.

As observed for the densities at 28 curing days, the increase in the reinforcement percentage also caused a significant bricks density reduction after aging, linked to the density of the lignocellulosic material and the loss of adhesion between reinforcement and matrix (Castro et al. 2017; Barbosa et al. 2019).

Table 9 shows the bricks average apparent porosity values, before and after accelerated aging, for each treatment, as well as the waste-produced-bricks average value variation compared to the control ones. Only the treatments with 1.5% coffee husk and 1.5% bamboo at 28 curing days showed no significant effect compared to the control treatment. The other treatments presented an increase in porosity ranging from 6.99 to 18.50%. For the aged bricks, a significant effect was noted for all treatments, with porosity values increase ranging between 4.48 and 21.53%. The increase in porosity is related to matrix-reinforcement interaction, the presence of extractives that affect the brick`s curing process and the greater need for water to produce bricks with agricultural waste, which forms pores in the brick (Almeida et al. 2013; Samia et al. 2015; Delannoy et al. 2020).

**Table 9** – Soil-cement-particle bricks apparent porosity

| Treatment | Apparent porosity (%) | Δ (%) | Apparent Porosity (Aged) (%) | Δ (%) |
|---|---|---|---|---|
| **1.5% R.H.** | 38.30 $^{(1,16)}$ * a | 10.22 | 44.00 $^{(0,57)}$ * b | 11.96 |
| **3% R.H.** | 37.18 $^{(1,47)}$ * a | 6.99 | 43.43 $^{(0,97)}$ * b | 10.51 |
| **1.5% C.H.** | 33.84 $^{(0,76)}$ ns a | -2.62 | 41.06 $^{(0,54)}$ * b | 4.48 |
| **3% C.H.** | 41.06 $^{(0,14)}$ * a | 18.16 | 46.73 $^{(0,61)}$ * b | 18.91 |
| **1.5% B.** | 34.47 $^{(1,17)}$ ns a | -0.81 | 43.26 $^{(0,61)}$ * b | 10.08 |
| **3%B.** | 41.18 $^{(0,94)}$ * a | 18.50 | 47.76 $^{(0,76)}$ * b | 21.53 |
| **Control** | 34.75 $^{(0,53)}$ a | | 39.30 $^{(0,58)}$ b | |

*Statistically differed by Dunnett test (α=0.05) from control treatment; ns Did not statistically differ by Dunnett test (α=0.05) from the control treatment. Averages followed by the same lower case letter in the line did not differ by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation. R.H. - Rice husk; C. H. - Coffee husk; and B - Bamboo.

For porosity, when comparing the bricks after 28 curing days with the aged ones on each treatment, it was noted that all treatments showed a statistical difference for the porosity index, with the aged bricks presenting the highest values due to the lignocellulosic particle expansion when absorbing water and shrinkage during the accelerated aging wetting and drying cycles, causing loss of adhesion between reinforcement and matrix, thus creating voids that increase bricks` porosity (Boonstra and Tjeerdsma 2006; Giroudon et al. 2019), as seen in Figure 3.

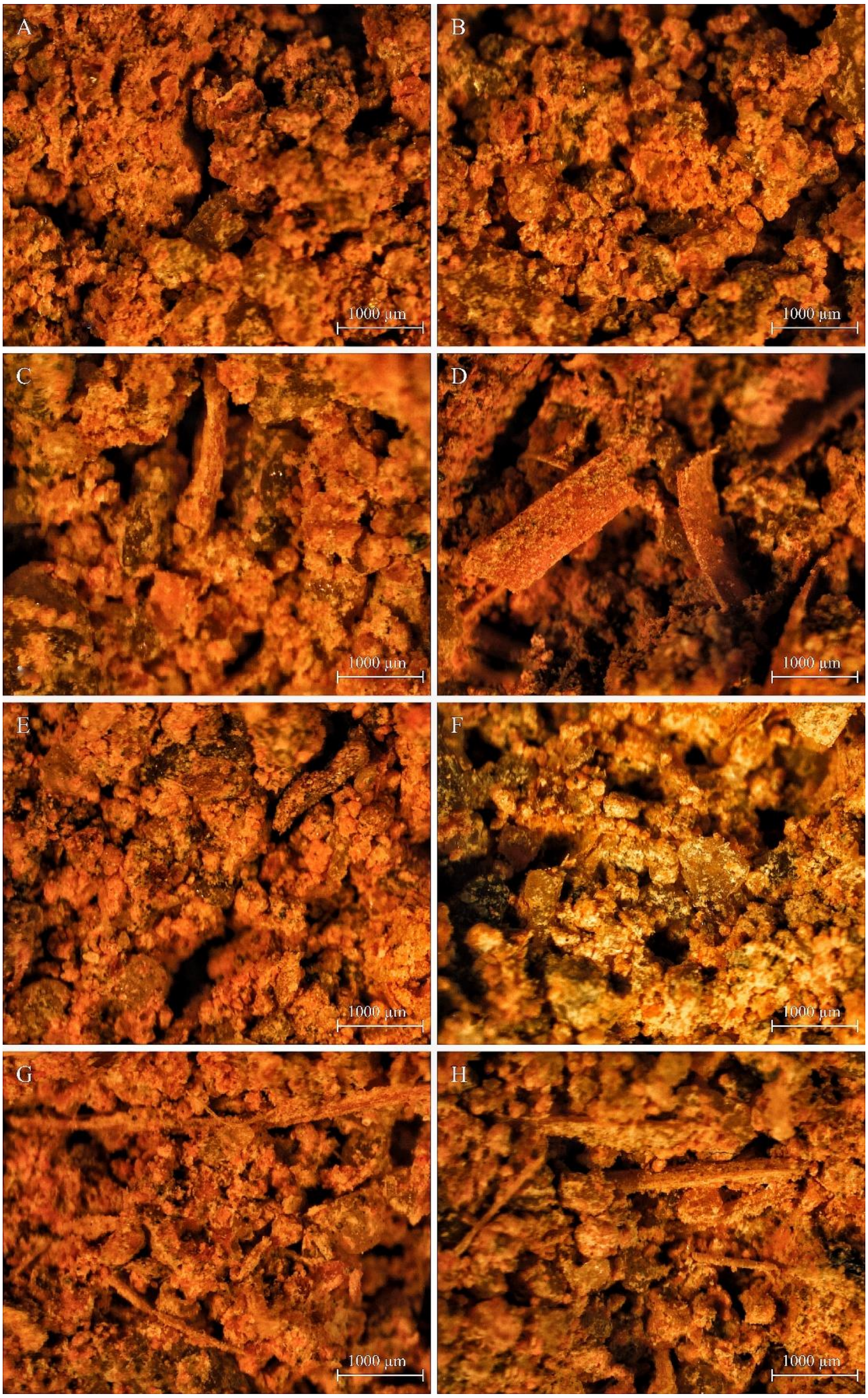


**Figure 3** - Optical microscopy image of soil-cement bricks at 28 curing days and after accelerated aging. A) Soil-cement brick control at 28 days; B) Aged soil-cement brick control; C) Soil-cement brick with 3% rice husk at 28 days; D) Aged soil-cement brick with 3% rice husk E) Soil-cement brick with 3% coffee husk at 28 days; F) Aged soil-cement brick with 3% coffee husk; G) Soil-cement brick with 3% bamboo at 28 days; H) Aged soil-cement brick with 3% bamboo.

Also, for bricks at 28 curing days and aged ones, a correlation between the waste (rice husk, coffee husk and bamboo) and the percentages (1.5% and 3%) was noted, with the bricks apparent porosity values presented in Table 10.

**Table 10 –** Bricks apparent porosity values as a function of waste and their percentages at 28 curing days and aged (%)

| Treatment | Rice Husk | Coffee Husk | Bamboo |
|---|---|---|---|
| | **28 curing days** | | |
| **1.5%** | 38.30 $^{(1,16)}$ Ab | 33.84 $^{(1,15)}$ Aa | 34.47 $^{(1,24)}$ Aa |
| **3%** | 37.18 $^{(1,47)}$ Aa | 41.06 $^{(0,14)}$ Bb | 41.18 $^{(0,94)}$ Bb |
| | **Aged** | | |
| **1.5%** | 44.00 $^{(0,57)}$ Ab | 41.06 $^{(0,54)}$ Aa | 43.26 $^{(0,61)}$ Ab |
| **3%** | 43.43 $^{(0,97)}$ Aa | 46.73 $^{(0,61)}$ Bb | 47.76 $^{(0,76)}$ Bb |

Averages followed by the same uppercase letter (in the column) and lower case (in the row) did not differ from each other by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation.

When evaluating the 1.5% and 3% percentages on each waste (rice husk, coffee husk and bamboo) for bricks at 28 curing days and aged ones, only the treatments with coffee husk and bamboo showed a statistical difference between the percentages evaluated for bricks production, with the treatments with 3% waste showing the highest porosity rates. The increase in the percentage of lignocellulosic particles results in their greater interlacing, generating less interaction with the cement matrix, as well as increasing porosity as a function of the particles lumen used, and lower densities observed for the coffee and bamboo husk (Table 4), thus directly affecting the composite`s porosity (Wei and Meyer 2015; Hamidon et al. 2019; Danso and Manu 2020).

When comparing the types of waste (rice husk, coffee husk and bamboo) on each percentage (1.5% and 3%), both for bricks at 28 curing days and aged ones, a significant effect on the apparent porosity was also observed. At 28 curing days, the treatment with 1.5% rice husk showed higher porosity compared to coffee husk and the bamboo one. For the aged bricks added with 1.5% waste, those with rice husk and bamboo were statistically similar, as opposed to coffee husk that showed a lower porosity rate. Overall, it could be noticed that coffee husk reduced bricks porosity at the 1.5% percentage, despite presenting a higher amount of extractives (Table 3), which affects cement curing (Almeida et al. 2013; Delannoy et al. 2020). However, it was observed that the correlation between lower density (Table 3) and smaller and more spherical geometries (Table 2) resulted in increased bricks compaction (Table 5), having a more outstanding effect on bricks porosity than the material`s chemical composition.

For 3% waste, the bricks added with rice husk, at 28 curing days and aged, showed less apparent porosity compared to those added with coffee husk and bamboo. Although rice husk provided initial higher porosity to the bricks compared to other waste when evaluated at 1.5% percentage, the increase in this waste`s percentage to 3% resulted in lower porosity for the bricks added with rice husk compared to other reinforcing materials. This result was due to the lower amount of extractives present in rice husk

(Table 3), which has a more pronounced effect when the particles are used at higher percentages, affecting the reinforcement-matrix interaction, as well as providing a higher density and lower water absorption for the material (Table 4) leading to a lower number of interlaced particles at higher percentages compared to the other two waste. The lower less water absorption avoids the pores generation in the cement matrix (Hwang and Huynh 2015; Hamidon et al. 2019; Barbosa et al. 2019).

Table 11 shows the average bricks water absorption values, before and after accelerated aging, for each treatment, as well as the waste-produced-bricks average value variation compared to the control ones.

**Table 11** – Soil-cement-particle bricks water absorption

| Treatment | Water Absorption (%) | Δ (%) | Water Absorption (Aged) (%) | Δ (%) |
|---|---|---|---|---|
| **1.5% C.A.** | 22.12 $^{(1,18)}$ * a | 10.99 | 25.79 $^{(0,31)}$ * b | 11.07 |
| **3% C.A.** | 23.90 $^{(0,73)}$ * a | 19.92 | 25.06 $^{(0,55)}$ * b | 7.92 |
| **1.5% C.C.** | 20.57 $^{(1,15)}$ ns a | 3.21 | 24.03 $^{(0,40)}$ ns b | 3.49 |
| **3,0% C.C.** | 22,73 $^{(0,22)}$ * a | 14,05 | 27,12 $^{(0,44)}$ * b | 16,80 |
| **1.5% B.** | 22.57 $^{(1,24)}$ * a | 13.25 | 24.78 $^{(0,47)}$ * a | 6.72 |
| **3%B.** | 22.72 $^{(2,02)}$ * a | 14.00 | 27.36 $^{(0,56)}$ * b | 17.83 |
| **Control** | 19.93 $^{(0,80)}$ a | | 23.22 $^{(0,31)}$ b | |

*Statistically differed by Dunnett test (α=0.05) from control treatment; ns Did not statistically differ by Dunnett test (α=0.05) from the control treatment. Averages followed by the same lower case letter in the line did not differ by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation. R.H. - Rice husk; C.H. - Coffee husk; and B - Bamboo.

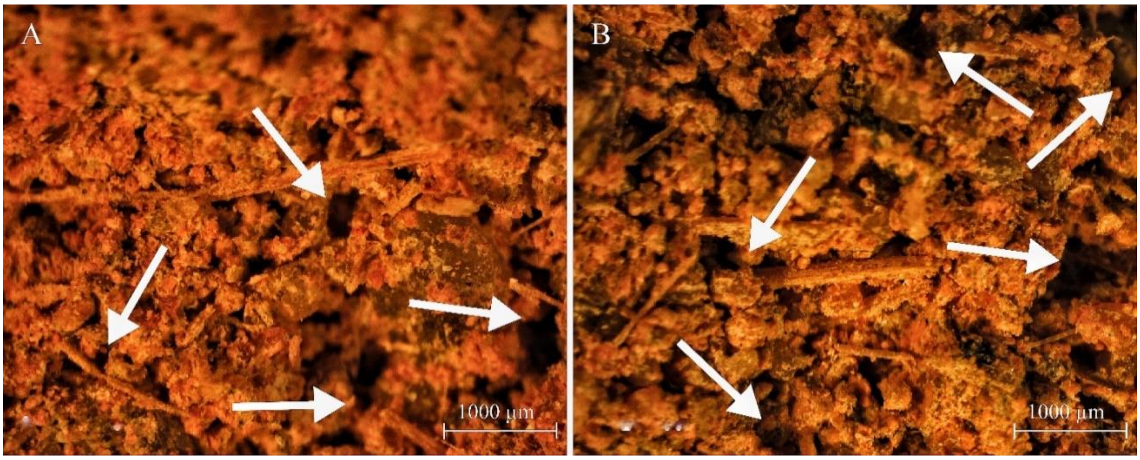


**Figure 4** - Optical microscopy image of soil-cement bricks with 3% bamboo at 28 curing days and aged A) Pores in the soil-cement bricks with 3% bamboo at 28 curing days; B) Pores in the aged soil-cement bricks with 3% bamboo.

For bricks water absorption values at 28 curing days, no correlation was observed between the waste (rice husk, coffee husk and bamboo) and the percentages (1.5% and 3%). For water absorption as a function of waste, no statistical difference occurred among the waste and the average values were 23.01;

21.65 and 22.65% for rice husk, coffee husk and bamboo, respectively. For water absorption as a function of waste percentages, no statistical difference between the percentages occurred and the average values were 21.75 and 23.12% for 1.5% and 3% percentages, respectively.

Interaction among the waste (rice husk, coffee husk and bamboo) and the two percentages (1.5% and 3%) was observed for the aged bricks. The water absorption values are shown in Table 12.

**Table 12** – Aged soil-cement-particle bricks water absorption values

| Treatment | Rice Husk | Coffee Husk | Bamboo |
|---|---|---|---|
| **1.5%** | 25.79 $^{(0,31)}$ Ab | 24.03 $^{(0,40)}$ Aa | 24.78 $^{(0,47)}$ Aa |
| **3%** | 25.06 $^{(0,55)}$ Aa | 27.12 $^{(0,44)}$ Bb | 27.36 $^{(0,56)}$ Bb |

Averages followed by the same uppercase letter (in the column) and lower case (in the row) did not differ from each other by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation.

Evaluating the percentages (1.5% and 3%) on each waste (rice husk, coffee husk and bamboo), it was observed that only coffee husk and bamboo presented a statistical difference and the highest absorption values were obtained for treatments with 3 % lignocellulosic material. Such higher absorption rate was due to the higher porosity of the composites caused by loss of adherence between the particles and matrix, as well as to the great lignocellulosic materials affinity with water, which intensifies at higher particles percentages (de Araujo et al. 2018; Barbosa et al. 2019).

When comparing the waste (rice husk, coffee husk and bamboo) on each percentage (1.5% and 3%), it was noted that the bricks produced with rice husk had a higher water absorption rate than the other treatments when using 1.5% waste, which were statistically similar. While for treatments with 3% waste, the coffee husk and bamboo were statistically similar, differing from rice husk, which had lower water absorption. Such result is linked to the presence of protective wax aiding the material's lower water absorption (Table 4) and the lower amount of extractives found in rice husk, as they inhibit matrix curing around the particles, which increases the number of pores and adherence loss of composite phases (Onuaguluchi and Banthia 2016; Wang et al. 2019). It is also linked to a higher density of material (Table 4), which requires fewer particles for a given pre-defined reinforcement material mixture, and hence fostering lower -OH groups availability for water binding, as well as by the lower porosity values of this treatment (Table 10).

Table 13 shows the average loss of mass values by brick immersion, before and after accelerated aging, for each treatment. It also shows the waste-produced-bricks average value variation compared to the control ones. For loss of mass by bricks immersion at 28 curing days, no significant effect was observed for the treatments with 1.5% rice husk and 3% bamboo compared to the control. The other treatments showed a loss of mass decrease ranging from -12.18 to -25.21%. Waste addition to composites provided greater matrix stability, so a soil-cement bricks loss of mass reduction (Saleh et al. 2014; Barros et al. 2020b) was noted. For the aged bricks, no significant effect was noted in relation to the loss of mass for any treatment compared to the control. Such a result was due to the adherence loss between particle and matrix after aging, causing the loss of more material (Barbosa et al. 2019; Elahi et al. 2020).

**Table 13** – Loss of mass by soil-cement-particle bricks immersion

| Treatment | Loss of mass (%) | Δ (%) | Loss of mass (Aged) (%) | Δ (%) |
|---|---|---|---|---|
| **1.5% C.A.** | 4.52 $^{(0,08)}$ ns a | -3.42 | 7.00 $^{(1,34)}$ ns b | 9.20 |
| **3% C.A.** | 3.50 $^{(0,03)}$ * a | -25.21 | 9.77 $^{(0,46)}$ ns b | 52.42 |
| **1.5% C.C.** | 4.11 $^{(0,04)}$ * a | -12.18 | 7.20 $^{(2,17)}$ ns a | 12.32 |
| **3% C.C.** | 3.66 $^{(0,29)}$ * a | -21.79 | 9.72 $^{(1,57)}$ ns b | 51.64 |
| **1.5% B.** | 3.74 $^{(0,10)}$ * a | -20.09 | 7.65 $^{(1,40)}$ ns a | 19.34 |
| **3%B.** | 4.45 $^{(0,11)}$ ns a | -4.91 | 6.87 $^{(2,44)}$ ns a | 7.18 |
| **Control** | 4.68 $^{(0,20)}$ a | | 6.41 $^{(1,27)}$ a | |

*Statistically differed by Dunnett test (α=0.05) from control treatment; ns Did not statistically differ by Dunnett test (α=0.05) from the control treatment. Averages followed by the same lower case letter in the line did not differ by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation.

When comparing bricks at 28 curing days with the aged ones, it was observed that only the treatments added with 1.5% and 3% rice husk and 3% coffee husk showed statistically higher values when aged. Aging may have caused the rice husk wax layer degradation and chemical interaction with cement, fostering less adherence between the particles and, hence, greater loss of mass compared to brick at 28 curing days (Figure 5). The same may have occurred with the coffee husk extractives, which at a higher percentage (3%) damaged the bricks' stability (Teixeira et al. 2020; Danso and Manu 2020). It was also noted that the higher slenderness index of bamboo particles contributed to the lower loss of mass on bricks (Giroudon et al. 2019; Danso and Manu 2020).

According to ABCP (1986) and NBR 13553 (ABNT 2012e) standards, the soil-cement bricks loss of mass, after immersion and drying cycles, should not exceed 10%. Therefore, it was found that all treatments were approved in relation to this limit, even after the accelerated aging test.

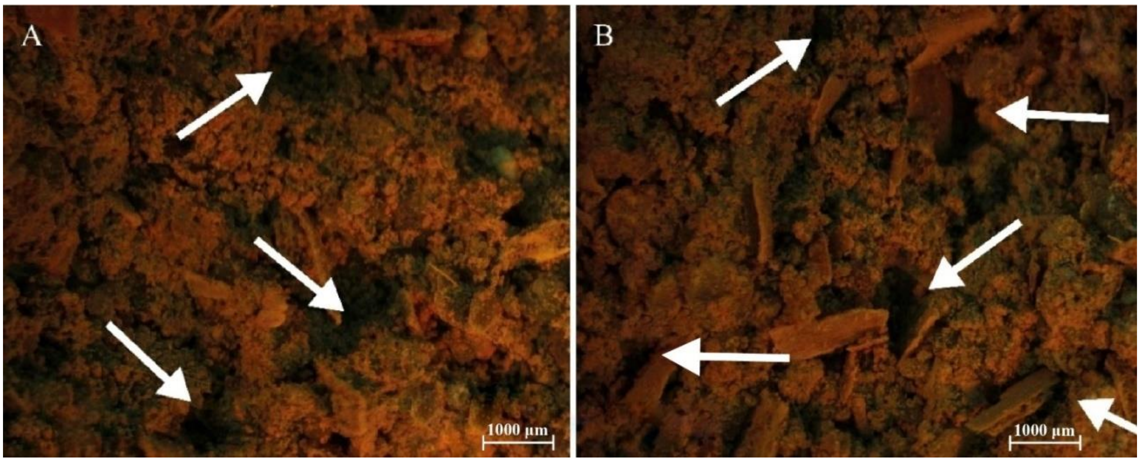


**Figure 5 -** Optical microscopy image of soil-cement bricks with 3% rice husk at 28 curing days and aged A) Fewer pores and greater interaction of rice husk particles and the matrix in soil-cement brick at 28

curing days; B) Higher number of pores and less interaction between the rice husk particles and matrix in aged soil-cement bricks.

The interaction was observed between the waste (rice husk, coffee husk and bamboo) and the two percentages (1.5% and 3%) applied on bricks at 28 curing days. The results for the loss of mass by immersion are seen in Table 14.

**Table 14** – Soil-cement-particle bricks loss of mass at 28 curing days (%)

| Treatment | Rice Husk | Coffee Husk | Bamboo |
|---|---|---|---|
| **1.5%** | 4.52 $^{(1,28)}$ Ac | 4.11 $^{(1,15)}$ Ab | 3.74 $^{(1,24)}$ Ba |
| **3%** | 3.50 $^{(0,73)}$ Ba | 3.66 $^{(0,22)}$ Ba | 4.45 $^{(2,02)}$ Ab |

Averages followed by the same uppercase letter (in the column) and lower case (in the row) did not differ from each other by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation.

For loss of mass by immersion, when evaluating the 1.5% and 3% percentages for each waste (rice husk, coffee husk and bamboo), it was noted that all treatments were statistically differentiated. For rice husk and coffee husk, the highest loss of mass values by immersion was noted when using 1.5% waste, due to greater soil stabilization by using more particles, as with the increase in the percentage of the particles, there was an improvement in the soil structure, causing a lower loss of mass (Jordan et al. 2019; Danso and Manu 2020). However, for bamboo, the highest average value was observed when 3% was used. Such result may be linked to bamboo`s long and thin particle geometry presenting a higher slenderness index (Table 2), which makes the interaction of bamboo particles in large numbers with the matrix difficult and produces composites with a higher porosity rate (Table 10), facilitating loss of mass and bricks degradation.

When comparing the waste (rice husk, coffee husk and bamboo) on each percentage (1.5% and 3%), significant loss of mass by immersion occurred. When using 1.5%, all waste were different from each other and the bricks added with bamboo presented the lowest loss of mass, followed by bricks added with coffee husk and rice husk. However, when using 3% waste, the bricks added with rice husk and coffee husk were statistically similar and differentiated from the bricks added with bamboo that presented the highest average value. Although initially the rice husk and coffee husk provided a greater loss of mass due to bamboo`s higher slenderness rate (Table 2), which improves matrix interaction, bamboo, at higher percentages, provided bricks with lower densities (Table 7) and higher porosity (Table 9) caused by greater particles interlacing due to their geometry, resulting in lower interaction with the matrix (Giroudon et al. 2019; Delannoy et al. 2020). Figure 6 shows the lower interaction between the bamboo particles and the matrix of bricks when 3% of particles are used compared to the bricks with rice and coffee husk.

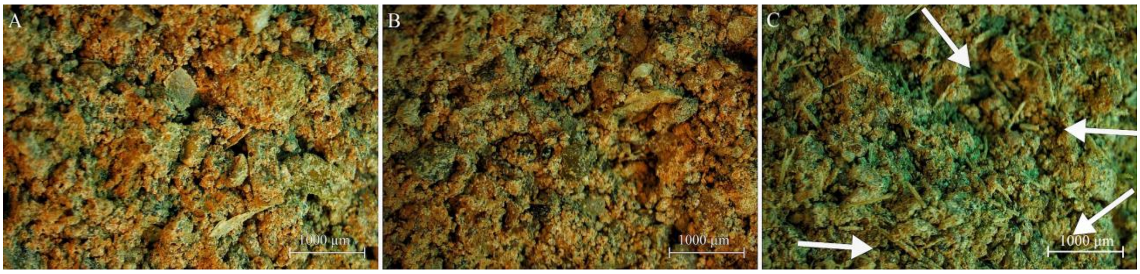


**Figure 6 -** Optical microscopy image of soil-cement bricks with waste at 28 curing days. A) Soil-cement brick with 3% rice husk at 28 curing days; B) Soil-cement brick with 3% coffee husk at 28 curing days; C) Soil-cement brick with 3% bamboo at 28 curing days.

For loss of mass by immersion on aged bricks, no interaction was observed between the waste (rice husk, coffee husk and bamboo) and the two percentages (1.5% and 3%). For the loss of mass as a function of the waste, no statistical difference among the waste were found and the average values were 4.01; 3.88 and 4.10% for the rice husk, coffee husk and bamboo waste, respectively. For loss of mass as a function of waste percentages, no statistical difference was found between the percentages and the average values were 4.12 and 3.87% for 1.5% and 3% waste, respectively.

### 3.3.2 Soil-cement bricks mechanical characterization

Table 15 shows the average compressive strength values for each treatment, before and after accelerated aging, as well as the waste-produced-bricks average value variation compared to the control ones.

**Table 15** – Soil-cement-particle bricks compressive strength

| Treatment | Compressive Strength (MPa) | Δ (%) | Compressive Strength (Aged) (MPa) | Δ (%) |
|---|---|---|---|---|
| **1.5% R.H.** | 1.75 (0.25) * a | -20.09 | 1.72 (0,07) * a | -16.10 |
| **3% R.H** | 1.63 (0.24) * a | -25.57 | 1.47 (0,05) * a | -28.29 |
| **1.5% C.H.** | 1.39 (0.08) * a | -36.53 | 1.19 (0,19) * a | -41.95 |
| **3% C.H.** | 0.80 (0.03) * a | -63.47 | 0.83 (0.03) * a | -59.51 |
| **1.5% B.** | 1.57 (0.21) * a | -28,31 | 1.33 (0.28) * b | -35.12 |
| **3%B.** | 1.23 (0.03) * a | -43.84 | 1.46 (0.10) * a | -28.78 |
| **Control** | 2.19 (0.29) a | | 2.05 (0.14) a | |

*Statistically differed by Dunnett test (α=0.05) from control treatment; ns Did not statistically differ by Dunnett test (α=0.05) from the control treatment. Averages followed by the same lower case letter in the line did not differ by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation. R.H. - Rice husk; C. H. - Coffee husk; and B - Bamboo.

For compressive strength, both for the bricks at 28 curing days and aged ones, all treatments presented significant effect compared to the control one. It was observed that the use of waste reduced the mechanical strength of soil-cement bricks. This is related to the higher porosity of bricks produced with lignocellulosic waste and their lower density since such factors directly influence the composites` mechanical properties (Kizinievič et al. 2018; Giroudon et al. 2019). The compressive strength values may be linked to the granular aspect presented by the bricks added with waste particles compared to the control brick (Figure 7) caused by reinforcement-matrix interaction, which fosters voids that assist on cracks propagation when submitting bricks to the compressive strength testing (Jordan et al. 2019; Danso and Manu 2020).

NBR 8491 (ABNT 2012f) standard establishes 2 MPa as the minimum value for compressive strength, while IS 1725 (IS 1982) standard establishes two compressive strength classes for cement-produced-bricks, with 1.96 MPa for class 20 and 2.94 MPa for class 30 as the minimum values. Thus, the treatments with lignocellulosic waste did not meet the trading standards. Only the control treatment, at 28 curing days and aged, exceeded the minimum value determined by NBR 8491 (ABNT 2012f) and IS 1725 class 20 standards (IS 1982).

Jordan et al. (2019), when studying the use of sugarcane bagasse ashes in soil-cement bricks with 1:7:3 and 1:6:4 cement: soil: ash ratios also noted compression values reduction when using vegetal waste as reinforcement, not meeting the trading standards. However, Khedari et al. (2005), evaluated the use of coconut fiber on soil-cement bricks production obtained an average 3.88 MPa compressive strength using a 5.75:1.25:2 soil:cement: sand ratio and 0.8 kg coconut fiber. Thus, an amount of cement greater than that established by ABCP (1986) for standard bricks production not added with vegetal particles is needed for soil-cement bricks production when adding vegetal particles.

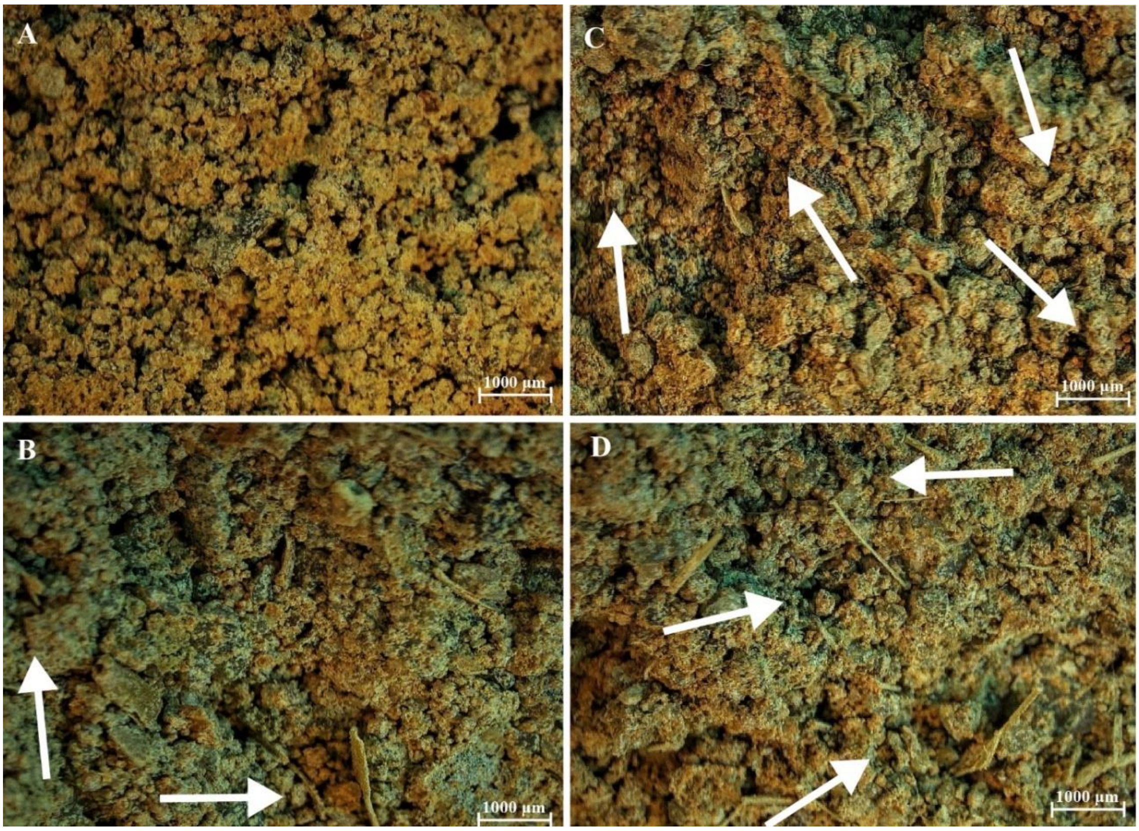

**Figure 7 -** Optical microscopy image of soil-cement bricks control and with 3% waste at 28 curing days. A) Soil-cement brick control at 28 curing days; B) Soil-cement brick with rice husk at 28 curing days; C) Soil-cement brick with coffee husk at 28 curing days; D) Soil-cement brick with bamboo at 28 curing days.

When comparing the bricks at 28 curing days with aged ones on each treatment, it was noted that only the treatment with 1.5% bamboo was statistically different and the bricks at 28 curing days presented the highest values. This was due to the slenderness index effect (Table 2) and the better interaction with the matrix at 28 curing days. However, it was less effective after aging, where the loss of adherence with the matrix occurred due to dimensional movement during the aging process wetting and drying cycles.

No interaction was noted between the waste (rice husk, coffee husk and bamboo) and the two percentages (1.5% and 3%) for bricks compressive strength at 28 curing days and aged. Figures 8 and 9 present the average compressive strength values as a function of lignocellulosic waste and percentages, respectively.

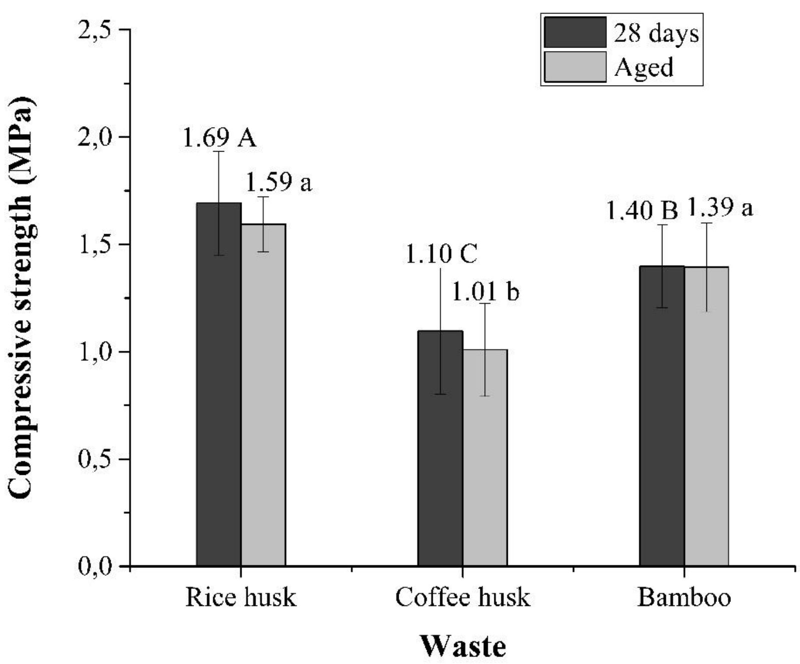


**Figure 8 –** Average compressive strength values as a function of waste added in soil-cement bricks production at 28 curing days and aged.

Averages followed by the same uppercase letter (28 curing days bricks) and lower case (aged bricks) did not differ from each other by the Scott-Knott average test at a 5% significance level.

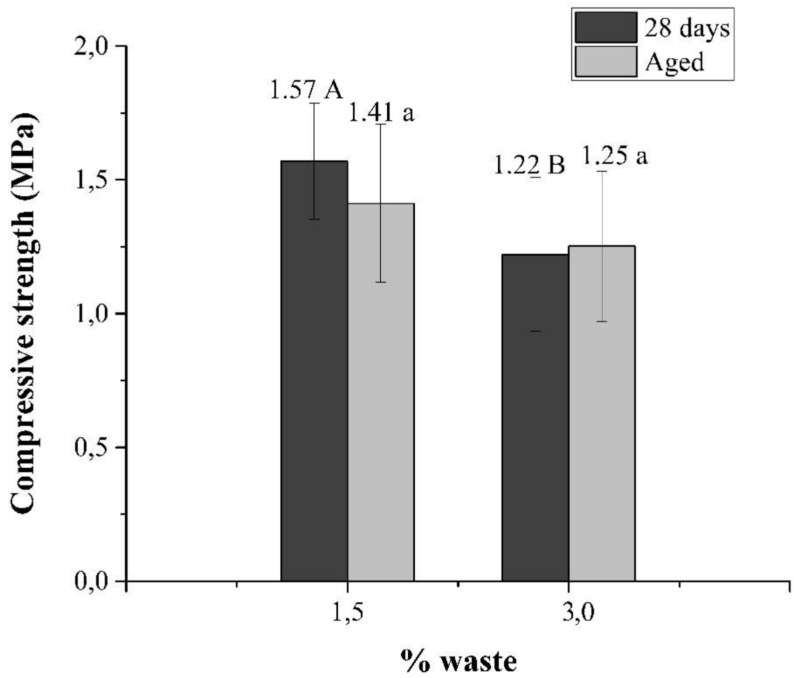


**Figure 9** - Average compressive strength values as a function of waste percentages added in soil-cement bricks production at 28 curing days and aged.
Averages followed by the same uppercase letter (28 curing days bricks) and lower case (aged bricks) did not differ from each other by the Scott-Knott average test at a 5% significance level.

When evaluating bricks compressive strength as a function of waste type at 28 curing days, the average values were statistically different for the three waste used. Bricks produced with rice husk presented the highest strength values, followed by the ones produced with bamboo and coffee husk, respectively. These results were due to the higher rice husk particles density (Table 4), which avoids a large number of particles for bricks production assisting on their compaction, a lower amount of extractives (Table 3) not affecting the cement curing as much as in other treatments (Diquélou et al. 2016; Delannoy et al. 2020), intermediate slenderness index (Table 2), and lower water absorption value (Table 4). The aforementioned combination provided better interaction with the matrix and a greater compression test performance for bricks. For bamboo particles, despite presenting the highest slenderness index, important to reinforcement-matrix interaction assistance (Giroudon et al. 2019; Barbosa et al. 2019), also presented intermediate density and amount of extractives and the highest water absorption among the lignocellulosic particles studied.

However, when evaluating compressive strength as a function of waste for aged bricks, bamboo and rice husk were statistically similar. This was due to rice-particle-covering wax degradation that increased loss of mass (Table 13) as a function of the adhesion loss caused by particles` dimensional movement, as well as the great slenderness index effect on compressive strength test since it helps to maintain greater adhesion with the matrix, even with lignocellulosic particles dimensional movement during the aging test.

Bricks produced with coffee husk had the poorest performance when submitted to the compressive strength test, both at 28 curing days and after accelerated aging, due to greater amount of extractives (Table 3), lower particles density (Table 4), lower slenderness index (Table 2) and intermediate water absorption (Table 4).

Overall, the anatomical, chemical and physical characteristics of lignocellulosic particles presented significant and associated effects on bricks' compressive strength, despite a sharper reinforcement particles' slenderness index effect on the bricks compression property.

For bricks compressive strength evaluation as a function of waste percentages (Figure 9), statistical difference was noted between the percentages at 28 curing days, with the highest strength values obtained for the treatments added with 1.5% waste. Such factor is linked to an increase of bricks porosity with a larger amount of waste (Table 10), which eventually decreases the density (Table 8) and the bricks compaction level (Table 5), having a direct effect on their mechanical properties. Zak et al. (2016) noted that as the amount of lignocellulosic material increased, the bricks` compressive strength decreased. The authors linked the decrease in strength to greater pore formation with the addition of fibers.

No significant effect of reinforcement percentage was noted on aged bricks` compressive strength, which demonstrates the effect of dimensional movement and the matrix adhesion loss even at smaller lignocellulosic particle percentages.

### 3.3.3 Soil-cement bricks thermal characterization

Table 16 shows the average thermal conductivity values for each treatment, as well as the waste-produced-bricks average value variation compared to the control ones.

**Table 16** – Soil-cement-particle bricks thermal conductivity

| Treatment | Thermal Conductivity ($W.m^{-1}°C^{-1}$) | Δ (%) |
|---|---|---|
| **1.5% C.A.** | 0.215 $^{(0,025)}$ * | -44.33 |
| **3% R.H.** | 0.209 $^{(0,028)}$ * | -46.04 |
| **1.5% C.H.** | 0.331 $^{(0,015)}$ * | -14.56 |
| **3% C.H.** | 0.258 $^{(0,027)}$ * | -33.31 |
| **1.5% B.** | 0.286 $^{(0,012)}$ * | -26.21 |
| **3%B.** | 0.356 $^{(0,004)}$ * | -8.18 |
| **Control** | 0.387 $^{(0,017)}$ | |

*Statistically differed by Dunnett test (α=0.05) from control treatment; ns Did not statistically differ by Dunnett test (α=0.05) from the control treatment. Values in brackets correspond to the standard deviation. R.H. - Rice husk; C.H.- Coffee husk; and B - Bamboo.

For thermal conductivity, all treatments showed a significant effect compared to the control treatment. It was noted that the use of waste on soil-cement bricks production reduced thermal conductivity between -8.18 and -46.04%. An excellent result since the lower the brick's thermal conductivity, the lower the temperature exchange between the external and internal part of the building lowering energy costs with cooling/heating units (Calvani et al. 2020; Intaboot 2020).

The decrease in thermal conductivity may be due to higher porosity and lower density of bricks produced with lignocellulosic particles (Tables 7 and 9), as conductivity is a particle-to-particle energy transfer process throughout the system. A fragment receiving energy increases its vibration state and transfers energy to nearby fragments. Thus, the more fragments associated, that is, the smaller the pores between the materials, the faster this transfer occurs, causing higher thermal conductivity (Cunha et al. 2016; Balaji et al. 2017).

Interaction was observed between the types of waste (rice husk, coffee husk and bamboo) and the two percentages used (1.5% and 3%). The results for thermal conductivity are shown in Table 17.

**Table 17** – Soil-cement-particle bricks thermal conductivity ($W.m^{-1}°C^{-1}$)

| Treatment | Rice Husk | Coffee Husk | Bamboo |
|---|---|---|---|
| **1.5%** | 0.215 Aa | 0.333 Bc | 0.285 Ab |
| **3%** | 0.210 Aa | 0.260 Ab | 0.355 Bc |

Averages followed by the same uppercase letter (in the column) and lower case (in the row) did not differ from each other by the Scott-Knott average test at a 5% significance level. Values in brackets correspond to the standard deviation.

For bricks thermal conductivity, evaluating the 1.5 and 3% percentages on each waste used (rice husk, coffee husk and bamboo), it was noted that only rice husk did not show any statistical difference among all treatments. For coffee husk, the lowest thermal conductivity values were observed for bricks produced with 3% waste due to the bricks' higher porosity (Table 10). For bamboo, the lowest values were obtained for bricks produced with 1.5% waste. Although the bricks added with 3% bamboo presented higher porosity than the ones with 1.5%, from Figures 3 and 6, it was noted that they exhibited high matrix porosity, low reinforcement-matrix interaction and a high loss of mass (Table 14), which may have created cracks in the bricks' matrix, facilitating heat flow in bricks and reducing their thermal insulation ability (Vilela et al. 2020).

When evaluating the type of waste on each reinforcement percentage, the bricks with rice husk excelled, presenting the lowest thermal conductivity, which may be justified by its chemical composition, with the highest amount of lignin and ash (Table 3), as the higher amount of lignin combined with rice husk protective wax prevents the heat flow passage (Mimini et al. 2019; Calvani et al. 2020).

Khedari et al. (2005), evaluating the use of coconut fiber in soil-cement brick production, obtained a thermal conductivity decrease of up to 54%. The authors obtained 0.651 W.m-1°C-1 average conductivity. Sutcu et al. (2015), evaluating the use of marble waste (up to 30%) on fire clay brick production noted that a thermal conductivity decrease from 0.97 to 0.40 W.m-1°C-1. Doubi et al. (2017), evaluated bricks produced with different Shea butter percentages (0, 2, 4, 6, 8 and 10%) and observed that it generated pore, hence improving thermal insulation properties.

According to NBR 15220-2 (ABNT 2008) standard, the ceramic bricks thermal conductivity should vary from 0.7 to 1.05 W.m-1°C-1 between 1.0 and 2.0 g/cm³. Thus, all treatments presented lower thermal conductivity than those determined for ceramic bricks, making soil-cement bricks an excellent option for environments that require better thermal insulation.

## 4. CONCLUSION

The anatomical, chemical and physical characteristics of lignocellulosic particles showed significant and interlinked effects on soil-cement bricks properties, with the anatomical and physical characteristics more effective at lower concentrations and the lignocellulosic materials chemical composition more effective at higher concentrations.

The increase in lignocellulosic waste percentages decreased the bricks' mechanical strength and increased their porosity and water absorption. However, it decreased density and improved loss of mass and thermal insulation.

The use of lignocellulosic materials on soil-cement bricks production, regardless of the waste type and its concentration caused a sharp composite thermal conductivity decrease.

Bricks produced with rice husk obtained the best results for mechanical and thermal properties, and were also among the best treatments for physical properties, excelling among the lignocellulosic waste as an alternative raw material source for soil-cement bricks production. Bricks produced with 1.5% rice husk obtained the highest compressive strength values and the ones with 3% rice husk had the lowest physical properties values.

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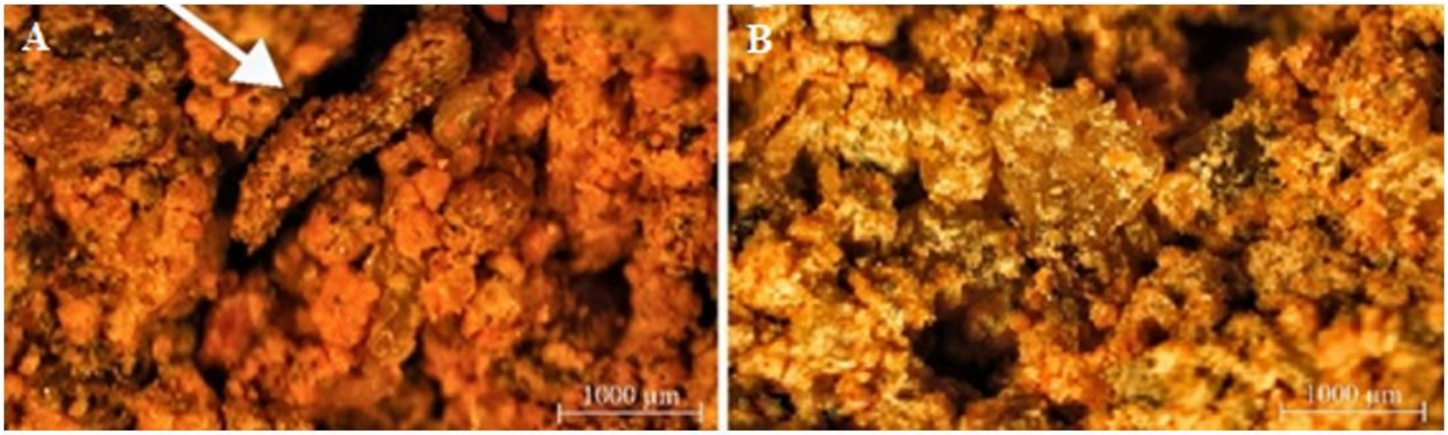
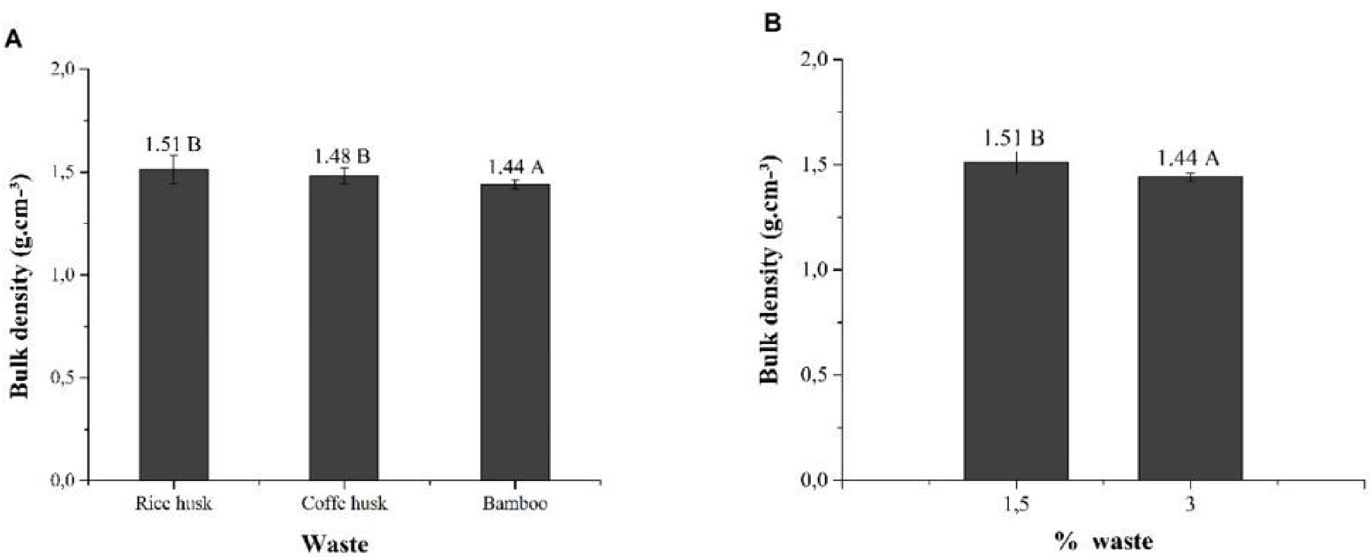
# Figures




## Figure 1

Optical microscopy image of aged and non-aged soil-cement bricks with 3% coffee husk. A) Coffee husk particle not adhered to the aged bricks matrix; B) Brick with coffee husk at 28 curing days.




## Figure 2

Bulk density A) as a function of waste type, and B) as a function of waste percentage. Averages followed by the same letter did not differ from each other by the Scott-Knott test at a 5% significance level.

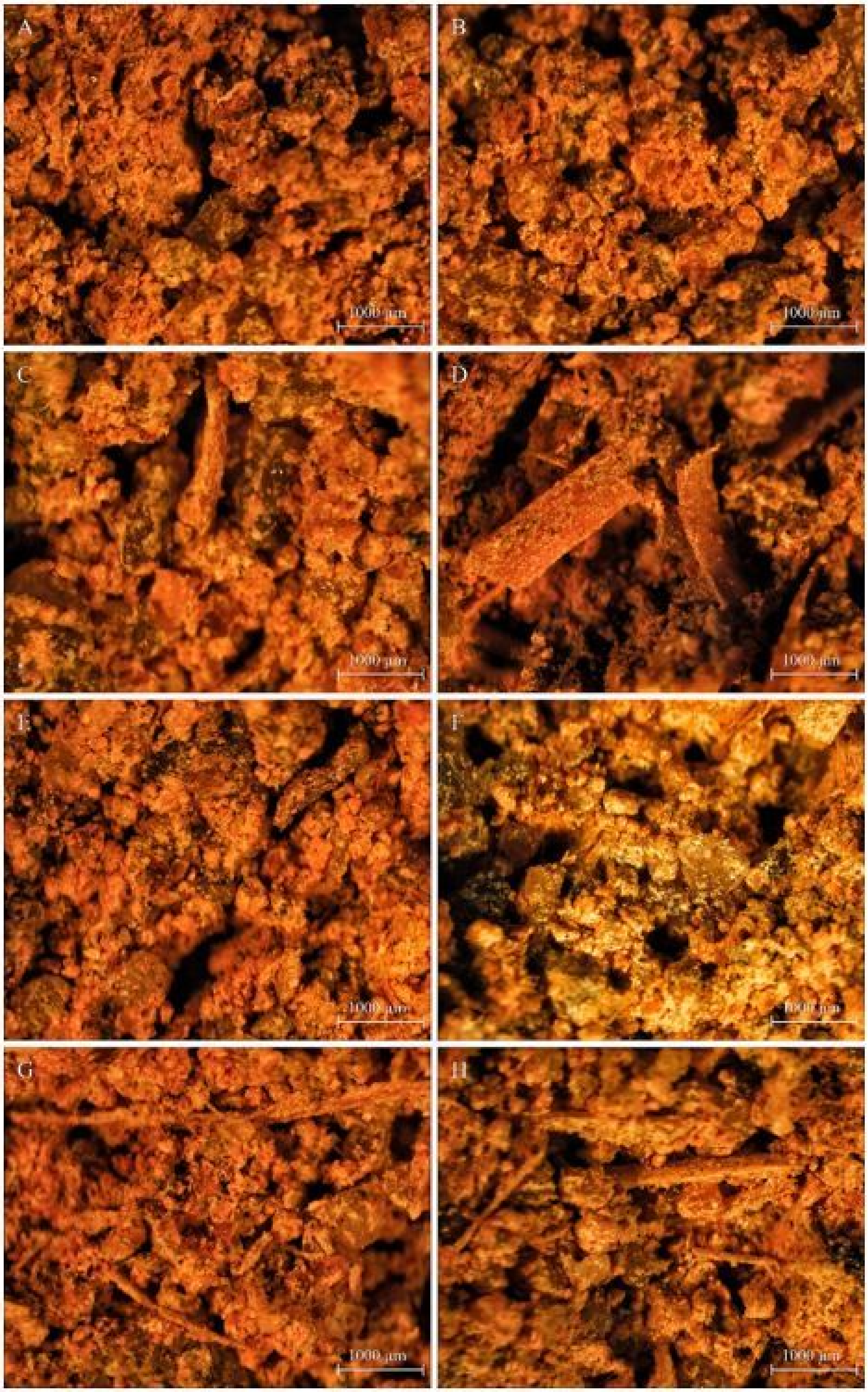



**Figure 3**

Optical microscopy image of soil-cement bricks at 28 curing days and after accelerated aging. A) Soil-cement brick control at 28 days; B) Aged soil-cement brick control; C) Soil-cement brick with 3% rice husk at 28 days; D) Aged soil-cement brick with 3% rice husk E) Soil-cement brick with 3% coffee husk at 28 days; F) Aged soil-cement brick with 3% coffee husk; G) Soil-cement brick with 3% bamboo at 28 days; H) Aged soil-cement brick with 3% bamboo.

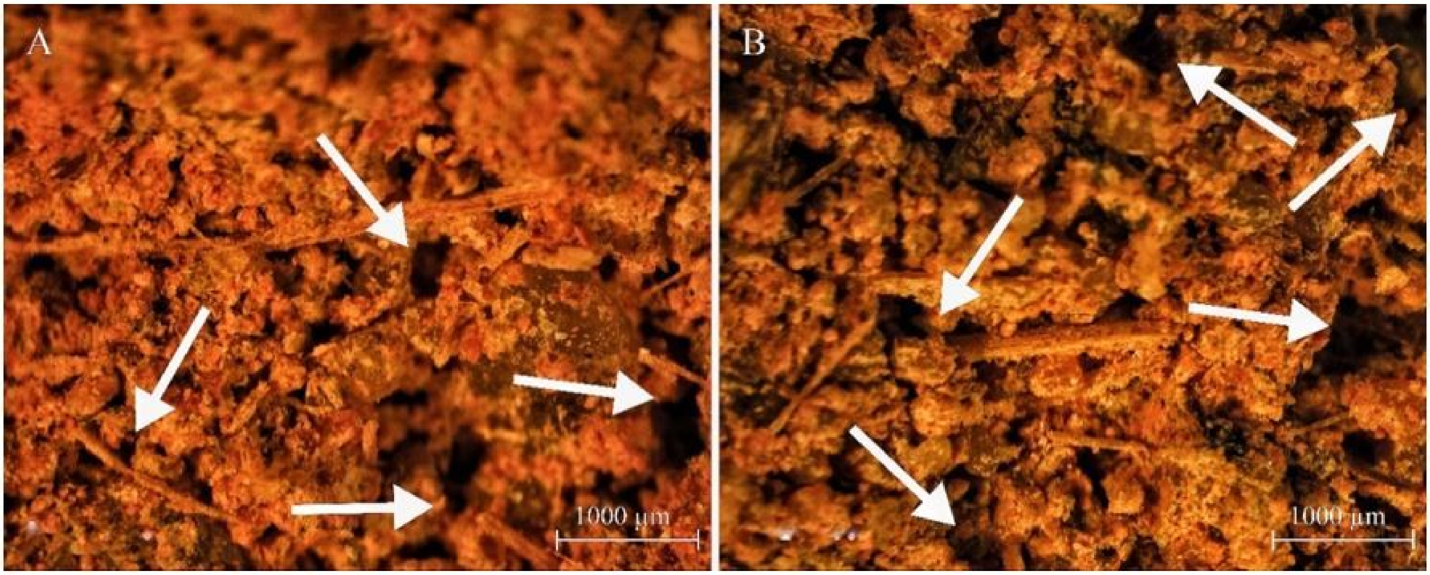



**Figure 4**

Optical microscopy image of soil-cement bricks with 3% bamboo at 28 curing days and aged A) Pores in the soil-cement bricks with 3% bamboo at 28 curing days; B) Pores in the aged soil-cement bricks with 3% bamboo.

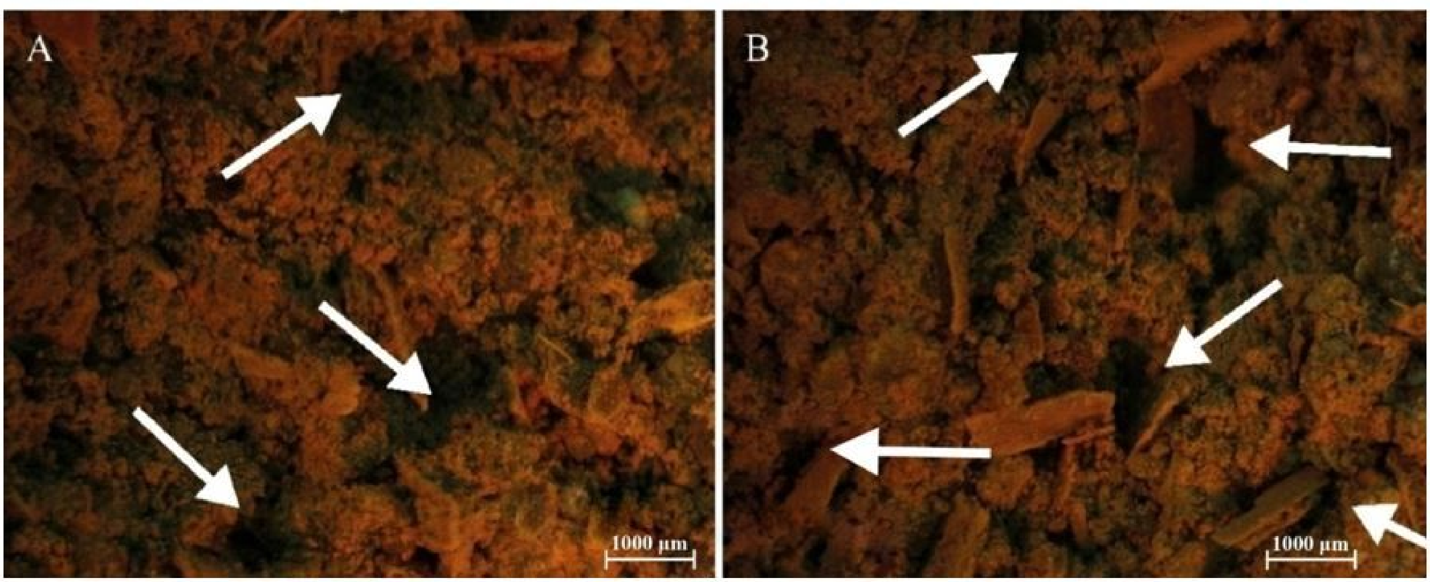



**Figure 5**

Optical microscopy image of soil-cement bricks with 3% rice husk at 28 curing days and aged A) Fewer pores and greater interaction of rice husk particles and the matrix in soil-cement brick at 28 curing days; B) Higher number of pores and less interaction between the rice husk particles and matrix in aged soil-cement bricks.


**Figure 6**

Optical microscopy image of soil-cement bricks with waste at 28 curing days. A) Soil-cement brick with 3% rice husk at 28 curing days; B) Soil-cement brick with 3% coffee husk at 28 curing days; C) Soil-cement brick with 3% bamboo at 28 curing days.

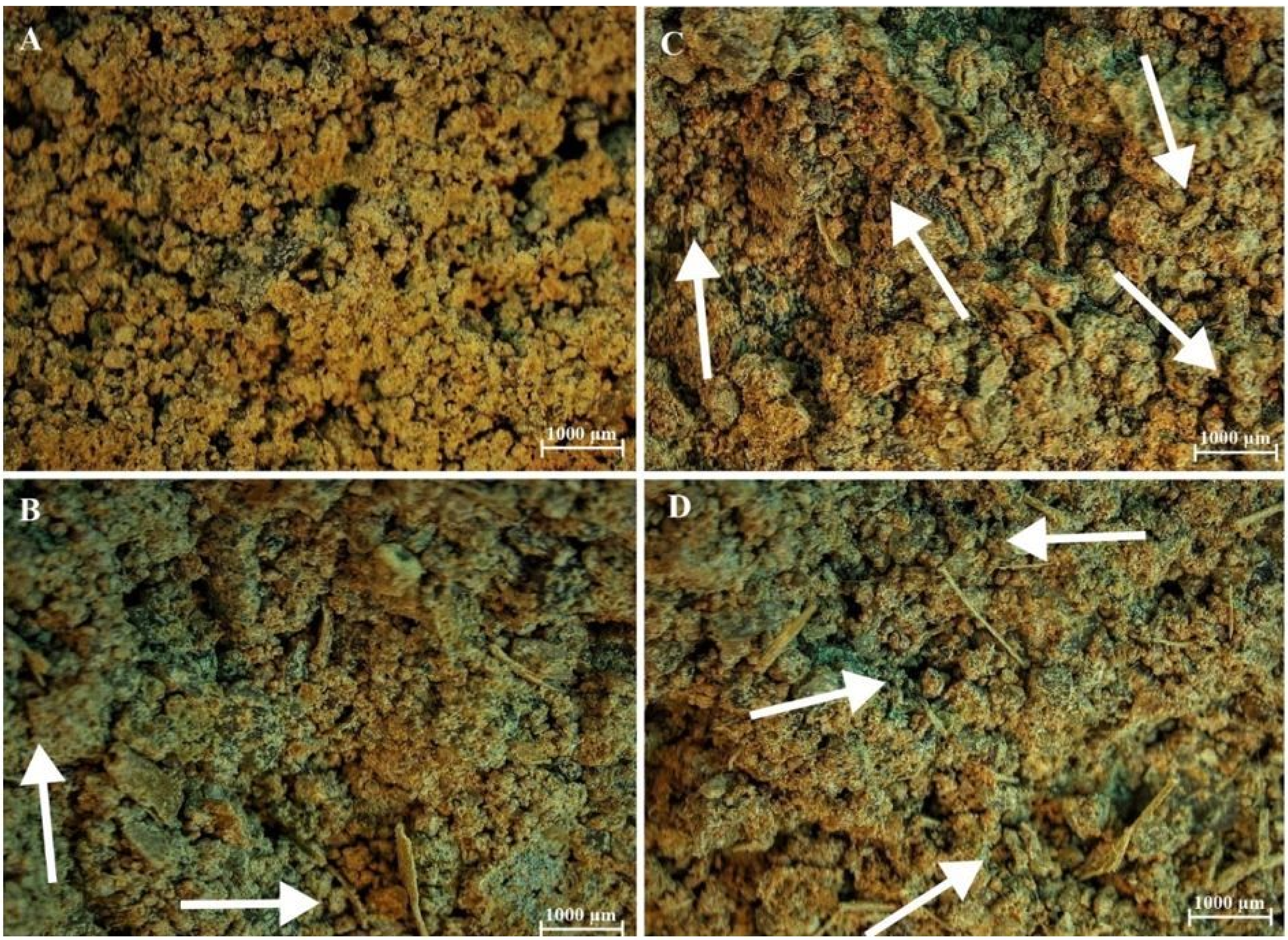



**Figure 7**

Optical microscopy image of soil-cement bricks control and with 3% waste at 28 curing days. A) Soil-cement brick control at 28 curing days; B) Soil-cement brick with rice husk at 28 curing days; C) Soil-cement brick with coffee husk at 28 curing days; D) Soil-cement brick with bamboo at 28 curing days.

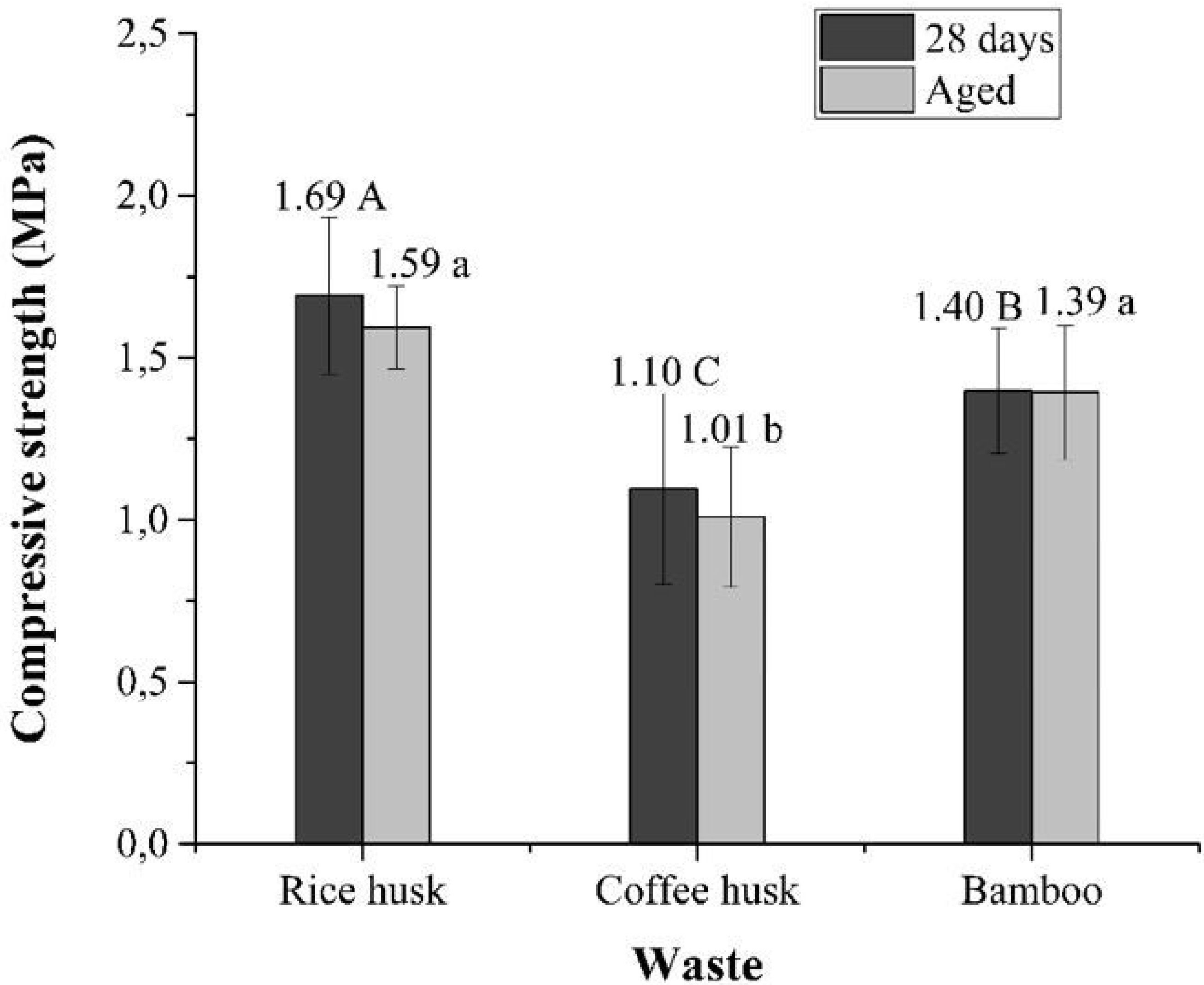



**Figure 8**

Average compressive strength values as a function of waste added in soil-cement bricks production at 28 curing days and aged.

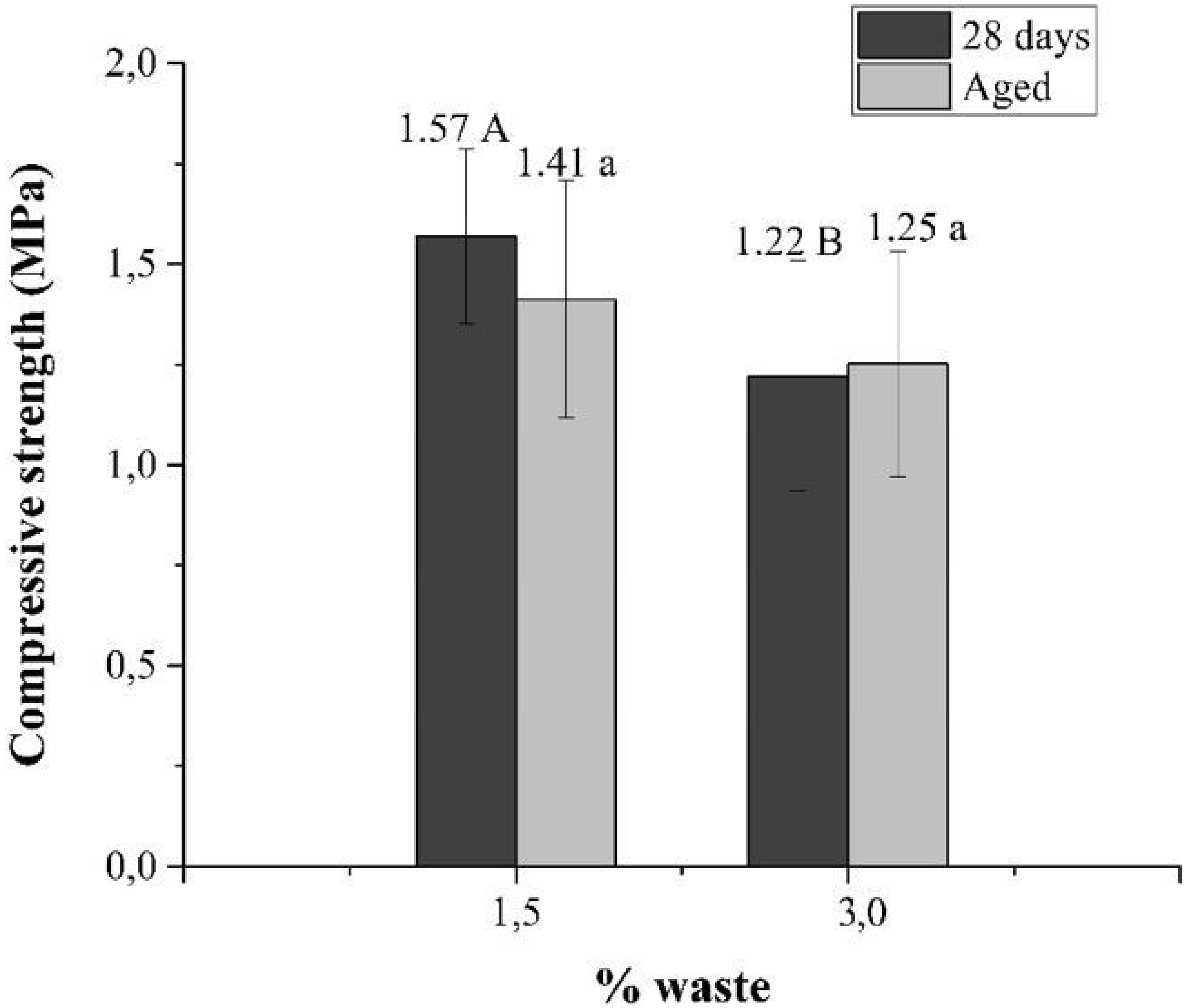



**Figure 9**

Average compressive strength values as a function of waste percentages added in soil-cement bricks production at 28 curing days and aged. Averages followed by the same uppercase letter (28 curing days bricks) and lower case (aged bricks) did not differ from each other by the Scott-Knott average test at a 5% significance level.