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Ceramic composite reinforced with agroindustrial waste

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Abstract

The field of materials engineering has been widely studied with the aim of obtaining new products from alternative raw materials and, in order to achieve success in these discoveries, it is necessary a careful analysis of the properties of these employed materials, as well as their applicability. The purpose of this review article is to list researches that used agroindustrial waste in ceramic composites, mainly vegetable fibers applied as reinforcement in ceramic matrix or, when in the form of ash, incorporated in soil-cement composites. These in natura residues proved to be efficient on the improvement of properties such as shearing, resistance to traction and compression, stabilization to mechanical efforts and, when thermally processed, inserted in composites in the form of ash, contributing to the reduction of porosity, improving density or acting as pozzolanic material. The investigation of both applications resulted in benefits to the physical, chemical, and mechanical properties of the ceramic product.

Keywords: Vegetable fibers. Pozzolanic ashes. Filler effect. Sustainable technology.

1. INTRODUCTION

The scientific knowledge on ceramic products, alongside the need to develop sustainable technologies, makes essential the study of materials that are technically suitable for production processes, especially in the industrial sector.

The use of soil as a ceramic building material is widely used over the years and achieved great evolution (Lamon, 2020). In ancient times it was common to make building blocks using a mixture of clay material, water, and straw, followed by molding and baking in the sun. The main disadvantage of this type of material is its sensitivity to water, which can cause the material disintegration and collapsing of the structure – as well as being affected by contraction and expansion – which can lead to cracks under adverse climatic conditions and low abrasion resistance. These disadvantages can be controlled using stabilizing additives such as asphalt, bitumen, lime and cement. Bitumen acts on impermeable soil grains, filling the capillary channels of the pores (Lazo-Renko et al., 2019). Lime and cement react with clay to form stable hydrated compounds (Lima & Iwakiri, 2019).

Ceramic composites are formed by two different phases (matrix / reinforcement) that act simultaneously, providing the necessary properties for certain applications. The matrix has the function of distributing and transmitting the efforts applied to the material in addition to shaping the material. Reinforcement, on the other hand, promotes a large part of the mechanical resistance to the material, especially in relation to the tensile strength (Leonel et al., 2017).

Several researches have been carried out in the last decades on materials applied as reinforcement in ceramic composites, analyzing mainly the mechanical properties of the composite. Among these materials, it is possible to highlight *in natura* vegetable fibers that improve the resistance of the product (Ruano et al., 2020) or, when thermally processed in ash form, increase its resistance and durability (Qudoos et al., 2019) providing a filler effect that creates a better padding in the pores of the structure or adds pozzolanic properties when used to replace commercial additives, such as cement (Hee Wong et al., 2020).

From this context, the relevance of the approach taken in this work is justified, which aims to present research that analyzed ceramic composites with the incorporation of vegetable fibers from the agroindustry. Such fibers were applied in several forms, including thermally processed in the form of ash. Some results stand out as propellants of alternative technology and sustainable practices.

2. REINFORCED COMPOSITE WITH AGROINDUSTRIAL WASTE

Clay and sandy soils are the basis of a ceramic matrix. Clays are aluminosilicates, consisting of alumina (Al_2O_3) and silica (SiO_2), which contain chemically bound water. They have some common impurities such as compounds (usually oxides) based on barium, calcium, sodium, potassium and iron and even organic materials (Hossain et al., 2018).

Research over the years has shown several types of agroindustrial waste added to the ceramic composite for improvements in its mechanical structure, such as the addition of vegetable fibers from coconut or sisal, which prevent the formation of cracks during the drying process in addition to reducing the soil density content, improving the load-deformation response by mechanically interacting with soil particles (Gutiérrez-Orrego et al., 2017).

The strength and deformability characteristics of the reinforcement material have a great influence on the stress versus deformation behavior of the reinforced soil. Thus, the fibers begin to exert an effective action within the soil mass when it is subjected to external efforts. The use of vegetable fiber provides a uniform homogeneity in which the isotropy of efforts is maintained, in addition to improving soil ductility, increasing shear resistance, better erosion control, facilitating vegetation development and reducing shrinkage in case of expansive soil (Bordoloi & Sekharan, 2017).

For Tang et al. (2010) after loading, normal soil tensions result in fiber deformation, which induces the mobilization of traction stress and, consequently, gives greater strength. The fiber is surrounded by interconnected soil particles, which contributes to the adhesion and friction force between the fiber and the soil matrix.

Anggraini et al. (2015) performed tests with coconut fiber mixed with soft soil treated with limestone. The results revealed that both the tensile strength and the compressive strength increased with the addition of coconut fiber, in addition to increasing the curing time.

Taallah & Guettala (2016) investigated the mechanical and physical properties in blocks of pressed and stabilized soil with lime and date palm fibers. The objective was to evaluate the influence of date palm fibers not treated and treated with sodium hydroxide (NaOH) on the properties of the blocks, verifying the compressive strength, tensile strength, absorption, density and thermal conductivity. The fibers were chemically treated using an alkaline solution to improve the fiber / matrix bond and increase mechanical strength. For the authors, the effect of treatment with concentrations of NaOH (0-9%), revealed a high interfacial adhesion and tension between the date palm fiber and the matrix. The apparent density of the block filled with treated and untreated fibers was lower than that of the block without fibers and the addition of fibers increased the water absorption of the block. The results indicated that, despite the resistance values of the treated fibers being slightly higher than that of the block filled with untreated fibers, the treatment on the surface of the fibers did not improve the adhesion between the fiber and the matrix and consequently interfered in the resistance.

Danso et al. (2015) studied the properties of ceramic blocks produced from soils stabilized with fibers from agricultural residues. In laboratory trials, the contents of density, water absorption and erosion were verified in soil blocks made with two types of soil (red - R and brown - B) and with three types of fiber (sugarcane bagasse, palm oil bagasse and coconut shell). It was observed that the density of the blocks decreased with the increase of the fiber in both types of soil, which was already expected since the fibers have a lower density compared to the soil.

The aforementioned authors found that greater water absorption from the blocks occurred with an increase in the fiber content, being able to attribute the amount of water absorbed by the fiber cellulose and the amount of cellulose material in which the absorbent nature of the fibers creates on the ground, generating a greater volume of hollows and allowing more water to be absorbed. In relation to erosion, there was a reduction for reinforced blocks compared to blocks not reinforced with fibers. Thus, the increase in resistance can be explained by the ability of the fibers to protect soil particles, thus reducing the effect of erosion.

The advantages of adding plant aggregates were also highlighted by Laborel-Préneron et al. (2016). When adding vegetable fibers as reinforcement in ceramic matrix (soil-cement-fiber) it was possible to observe that the mechanical behavior of the block starts to depend on several factors such as: fiber properties (type, elasticity module, tensile strength), geometry and aspect ratio; matrix properties (water / cement ratio, water / soil ratio, granulometry of the sand fraction, modulus of elasticity and presence of chemical and mineral additives); fiber content; orientation and distribution of fibers and fiber-matrix adhesion.

3. THE USE OF CEMENT AS A BINDER IN CERAMIC COMPOSITE

The use of cement in soil stabilization aims to improve the physical and mechanical characteristics and greater stability relative to the variation of the water content. Cement is an alkaline substance composed mostly of calcium silicates and aluminates which, during the reaction with water, release calcium hydroxides, giving rise to hydrated crystalline compounds and gel. These crystalline compounds create structures that give resistance to the material, while the cement gel develops spontaneously over the mineral surface, attaching itself to the oxygen ions exposed in the silicates and incorporating free calcium ions into a superstructure formed by the grouping of silicates (Ahsan & Hossain, 2018).

Wei-Ting et al. (2013) studied the microstructure of composites made from cement with various forms of rock wool particles and their morphology. The studies showed that quartz and calcium hydroxide were formed more significantly in the paste containing rock wool particles than in the control species and the inclusion of the wool particles in the composites contributed to form a denser microstructure.

The presence of minerals from the grains and the hydration of the cement are responsible for an increase in the compressive strength and stiffness. The degree of bonding depends on the volume occupied by the cement (bonding density), if these bonds have chemical properties similar to those of the cement used in the mixture. However, the geometry of the bonds and their dispersion in the granular medium depends on the amount of water available when the hydration of the cement is started. When small amounts of water are used in the mixture, the formation of concentrated bonds is expected and when large amounts of water are used, hydrated minerals are dispersed over the surfaces of the grains to form crystals and the overall texture of the material is more homogeneous (Ribeiro et al., 2016).

4. AGROINDUSTRIAL WASTE APPLIED IN SOIL-CEMENT MATRIX

Sasui et al. (2018) considered the need to use cement in ceramic blocks for better soil stabilization, since with the mixture hydration reactions of silicates and aluminates present in the cement occur, forming a gel that fills part of the hollows in the mass and joins the adjacent grains of the soil, giving it initial resistance and, in parallel, ionic reactions occur that cause the exchange of cations of the clay-mineral structures of the soil with the calcium ions from the hydration of the added cement.

Mostafa and Uddim (2016) studied a soil-cement block reinforced with fiber extracted from the trunk of the banana tree. The results indicated that the fiber-reinforced blocks had the highest tensile strength compared to the fiber-free block. There was an increase in the final stresses and in the maximum displacement in the failure of the blocks reinforced with fibers in comparison with the non-reinforced blocks due to the presence of the fiber absorbing stresses (Figures 1a and 1b). The non-reinforced blocks exhibited a sudden failure in all instances, while the fiber-reinforced blocks suffered a gradual failure. The load-deflection responses of the samples reinforced with fibers were different from those not reinforced (Figure 1c).

Ranjitham et al. (2019) also evaluated the soil-cement block with the banana fibers added in small pieces randomly oriented in the mixture and the results confirmed that the flexural strength was higher in the reinforced blocks.

Figure 1. Ceramic block not reinforced (a) and reinforced with fiber (b) under the same tension; Graph Tension x Deflection of the block reinforced with fibers in different mm (c). Source: Mostafa and Uddim (2016).

Ferreira and Cunha (2017) evaluated the technical quality of soil-cement blocks with the addition of plant residues, by the combination of destructive and non-destructive tests. The authors used a predominantly clayey soil, cement and residues of rice and brachiaria (Brachiaria brizantha) husks treated with hydrated lime. The blocks were submitted to destructive tests (water absorption and simple compression) and non-destructive tests (ultrasound) for their physical-mechanical characterization. The results obtained confirmed the positive effect on the mechanical stabilization process (pressing) and chemical stabilization (use of cement) on the quality of the blocks manufactured with the incorporation of waste, constituting an adequate alternative to the traditional block (manual molding).

Castro et al. (2019) evaluated the soil-cement block with coffee husk particles (Coffea arabica L.) in partial replacement for cement, in which the increase in the husk content caused increases in water absorption and the thermal conductivity found evidenced its potential insulation to improve the thermal comfort of buildings.

Studies with corn fiber indicated that the addition of fibers improved the mechanical properties, including compressive strength, tensile strength, ductility, toughness and stiffness (Tran et al., 2018) and studies of stabilized blocks reinforced with fibers of treated (T-PALF) and untreated (N-PALF) pineapple leaves also proved effective in terms of flexion and compression resistance of blocks reinforced with T-PALF. In this study it was also observed that water absorption increased with increasing fiber content, but those reinforced with N-PALF absorbed more water than those reinforced with T-PALF (Voudounon, 2018). For these applications it is necessary to analyze the mixture of the cementitious matrix with the fibers in relation to the ability to maintain its structural integrity during its lifespan. Thus, it becomes necessary to investigate mechanical performance over time.

Research on palm fiber reinforced blocks for thermal and mechanical properties demonstrated that the fibrous reinforcement had thermal conductivity and resistance to compression and improved thermal performance, which provides for future studies to investigate hygrothermal behavior and its impacts in the environment (Berrehail et al., 2018).

An increase in flexural strength is also seen in research conducted by Bouhicha et al., (2005) with barley straw and Villamizar et al. (2012) with cassava peel where it was observed that the ductility of the paste for the soil-cement block is greatly improved, since the bond formed by the fibers prevents the micro-cracks from expanding (Mostafa & Uddim, 2015).

Blocks with soil, cement, fiber and lime are also analyzed, in which cement has good workability, good resistance, provides better bonding of materials and the replacement of cement with proportions of lime provides benefits in increasing strength, as oxides of calcium behave like a gel, sealing pores in the sample (Danso & Manu, 2019).

Carrasco et al. (2019) cites several studies that confirm the effectiveness of the use of fibers in cement soil blocks, in which they do not prevent the formation of cracks, however, they control the spread of efforts throughout the mass of cement, benefiting the mechanical properties in the post-cracking state. However, it is worth highlighting the need for studies that analyze the incompatibility between the biomass of the chemical plant and cement for better conclusion of the results.

5. AGROINDUSTRIAL WASTE BENEFITED AND INCORPORATED IN SOIL-CEMENT MATRIX

The management of agroindustrial waste is an environmental challenge today. Thermally benefiting such residues and applying them in the form of ceramic composite ashes has been widely researched and, when the ash is predominantly siliceous, produced in the amorphous state and with adequate fineness, it can be used as a mineral addition in cementitious matrices depending on the chemical composition of the waste and the ash production process.

In order to use them as materials for the purpose of thermal insulation, it is essential to study the thermal properties of pure ash (Jafari & Jung, 2017). Brewery sludge ash, corn cob and used coffee beans were applied to obtain the filler effect on pore filling, in order to reduce the density and temperature of sintering (Andreola et al., 2020). In blocks containing palm oil ash with mixtures formulated from ultra-fine, unground ash and the mixture combined with cement and sand, results regarding the water absorption test met the specified minimum limit (Asrah et al., 2020).

Several researchers have used cane bagasse ash (Shafiq et al., 2014) and rice husk ash (Fundi et al., 2018) among other species that have demonstrated the effectiveness of these processed materials, which in the form of ashes, present themselves as pozzolanics in the formation of the microstructure of the soil-cement system, as well as the relationship between its microstructure and the physical, mechanical and chemical properties found in compounds from the effected mixtures.

5.1. The effects of sugarcane bagasse ash on soil-cement blocks

Sugarcane bagasse is the fibrous waste resulting from the extraction of sugarcane juice. Bagasse consists of approximately 50% cellulose, 25% hemicellulose and 25% lignin (Manikandan & Moganraj, 2014). The ash from the burning of sugarcane bagasse contains silica in its composition in contents above 60%. The silicon dioxide (SiO_2) with amorphous structure, depending on the burning conditions and its granulometry, has chemical and physical characteristics that can develop pozzolanic activity, which favors the application of ash as a pozzolan in partial replacement to Portland cement (Lamb et al., 2008).

To establish an average estimate of the generation of sugarcane bagasse residues, it is predicted that for each ton of processed cane, 270-290 kg of bagasse will be generated, which produces 23.8 kg of ash (Mansaneira et al., 2017). Tommaselli et al. (2011) reported that the amount of bagasse varied according to cane fiber content and approximately 25 kilograms of ash were generated for each ton of bagasse. Faria et al. (2012) evaluated the ecotoxicity of bagasse ash and considered it as a non-hazardous waste, however, its improper disposal results in an environmental impact.

James et al. (2016) analyzed the insertion of 4, 6 and 8% ash from sugarcane bagasse in soil blocks stabilized with 4 and 10% cement. The results showed that the addition of 8% ash to 4% cement content increases its resistance to compression and these values show a saving of 6% cement compared to the other combinations adopted. Therefore, to achieve a higher safety margin it is necessary to analyze other combinations and the durability aspect of the blocks must also be studied.

James and Pandian (2017) investigated several researches and concluded that the addition of sugarcane bagasse ashes in blocks decreased the resistance in the parameters with smaller proportions of cement, however, the use of the ashes revealed potential in terms of the thermal and electrical properties of the block. Jordan et al. (2019)

found that the loading effect did not occur as desired due to the presence of impurities and variable ash size among other factors. Although, the results regarding water absorption indicate an increase in the porosity of blocks without ash as well as in their compressive strength, and despite being lower than the blocks without ash, was still within the established limits.

Xu et al. (2019) consider that the application of ash has improved mechanical properties in the short term and long-term durability in cementitious matrices, however, it is worth noting that the heterogeneity of ash restricts large-scale application. Calcination is one of the most important influence factors on ash composition and there are advantages and limitations of different processing methods that affect pozzolanic activity.

5.2. The effects of rice husk ash on soil-cement blocks

Rice husk is a natural additive commonly used in both raw and ash forms as a stabilizer in cementitious matrices due to its pozzolanic properties. The ash from the rice husk has a great possibility of use, mainly for application in mortars and high-performance concretes, since the material is basically composed of silica and in the form of fine particles when mixed with calcium hydroxide and water, forms cementitious compounds.

Bezerra et al. (2011) verified the feasibility of using rice husk ash in settlement mortars and concluded that ash is characterized as pozzolanic material because it has amorphous behavior, high silica content and a higher pozzolanic activity index than that established by norm, giving it good reactivity and considering it suitable for use as a binder in mortar.

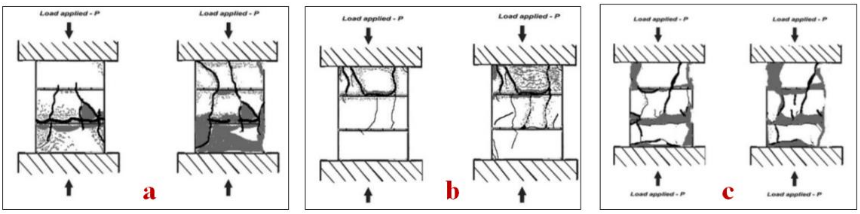
Studies presented by Thomas (2018) revealed that in a cementitious matrix, the rice husk ash can replace cement around 5 to 10% without compromising the workability, because above 10% the ash starts to demand more water reducing the workability, which can be corrected with the dosage of a plasticizer. The addition of ash to the matrix can be effective in reducing density and increasing resistance to compression (SUTAS et al., 2012). Also noteworthy is the use of ash added with nano-silica, which can contribute to high initial strength, in addition to increasing strength and long-term durability in cementitious matrices (Biricik & Sarier, 2014).

The ashes obtained during the combustion of the rice husk present variable structural shapes (amorphous and / or crystalline), depending on the type of burning (grill, fluidized bed), time and temperature of calcination (Angel et al., 2009). The effect of combustion conditions directly interferes with the properties of rice husk ash such as: specific mass, specific surface, color, and morphological structure (Bezerra et al., 2011).

Brahmachary et al. (2019) analyzed soil resistance with the addition of rice husk ash mixed with nylon fiber. The best results were in the proportion of soil mixture with 15% of rice husk ash and 1.0% nylon fiber. This proportion indicated an improvement in mechanical properties, as there was an increase in tensile strength by the addition of nylon fibers and a better adhesion effect by ash.

Sasui et al. (2018) compared the influence of raw rice husk (RRH) and rice husk ash (RHA) as stabilizers in compressive strength, stability and water absorption and volumetric contraction in samples of produced soil-cement block with sandy and clayey soil. The average compressive strength value demonstrated that the block containing RRH increased the strength and provided better connection with the ground, as no brittle deformation was observed under the loads and no perpendicular crack appeared in the joint (Figures 2).

Figure 2. (a) Application of loads to the specimen without the rice husk; (b) application of bulk loads with RRH; (c) applying bulk loads with RHA. Source: Sasui et al. (2018).



Another positive effect of the RRH was as a stabilizer and binder of the soil particles, which results in the efficient distribution of the loads induced throughout the material matrix. It is also observed that with the RRH stabilizer the sample did not deform completely, due to the flexibility of the RRH stabilizer and the interaction of the RRH with the soil particles. In addition, the material matrix functioned as a structural mesh under the compressive loads and, thus, prevented the complete deformation sample, while RHA reduced its reactivity in the formation of the bond with the soil, resulting in less resistance and complete deformation of the sample under compressive loads (Sasui et al., 2019).

Wei & Meyer (2016) studied two types of rice husk ash that differed mainly by the amorphic content of silica, one with 94.1% and the other with 90.5%. Both were used to replace cement parcels, and those substitutions with the ash of higher amorphic content were the ones that had the best results, both in the flexion tests and in the wetting and drying tests.

Mayooran et al. (2017) analyzed the feasibility of using rice husk ash with low (L-CCA) and high (H-CCA) carbon content in soil-cement blocks. It was observed that in the proportions with higher amounts of ash – due to the amount of silica in the mixture and reduction of calcium hydroxide (with the reduction of cement) – the hydrated calcium silicate gel (CHS) was limited, resulting in a deficiency of the compressive strength for the highest percentage of ash replacement in those blocks.

When comparing blocks with L-CCA and H-CCA, there was greater water absorption for blocks with high carbon content, since the finer particles of L-CCA have a better filling effect on the pores of the mortar structure of cement. The larger particle size of the H-CCA generated more pores in the block and this increase in the pore structure increases the permeability and the water absorption rate, and the smaller particle of the L-CCA tends to disperse better in the mixture. However, with a lower proportion of silica, there is no complete CH formation in CSH gel.

Prasara-A and Gheenwala (2017) presented several results from researchers who used rice husk ash to replace traditional components, demonstrating that different techniques in the generation of ash influence its pozzolanic characteristics and application, highlighting that the benefits involved technological, as well as environmental and economic aspects.

6. FINAL CONSIDERATIONS

Much of the resistance in ceramic composites is given by mixing the soil with materials that reinforce its molecular structure. Therefore, some fibers of agroindustrial waste have the purpose of absorbing the stresses that are applied to the composite and, consequently, improving its strength.

The fibers, being composed of large proportions of cellulose, act as a water absorber allowing a greater density of the composite and higher capacity to protect soil particles, also favoring the reduction of cracks, which can reduce the effect of erosion. Despite the advantages, it is necessary to analyze the physical, chemical, and mechanical performance of the composite over time, checking the structural integrity of the fibers in the mixture over the years.

When applying fiber to mixtures of soil and cement, the chemical compatibility of the plant's biomass and its reactions with the mixture should be checked for better conclusion of the results. As for performance such as thermal insulation, thermal conductivity and resistance to stress and compression, positive results are obtained in certain proportions of the mixture.

The thermal processing of the fiber favors the combustion of carbon and the release of volatile substances, preserving the ash with its mineral characteristics that can provide a differentiated technological performance. It is worth mentioning that the type of beneficiation processes, the calcination and grinding times directly interferes in the properties of the ash, which must be taken into account about its applicability.

The ash, when applied in mixtures of soil and cement, can be very effective for a better filler effect, reduction of density, increase in mechanical resistance, improving the workability of the mixture and, when it has pozzolanic characteristics, also favors the application in relation to the decrease in the amount of cement.

It is underlined that agroindustrial residues, due to their chemical composition, are mostly non-toxic. However, it is necessary to manage them, and their applicability in ceramic composites presents itself as a technical, economical, and environmentally viable solution.

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