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ORIGINAL ARTICLE

Valorization of fine wood dust waste to produce lightweight dense/porous bi-layered ceramic tile

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Abstract

The Brazilian wood furniture industry generates a significant amount of fine wood dust waste. In this work, a new lightweight dense/porous bi-layered ceramic tile was developed using fine wood dust waste as a substitute for ceramic tile paste by up to 10 wt% in the porous bottom layer. The bi-layered ceramic tile pieces were prepared by double uniaxial pressing and fired at 1235 ºC. The technical properties and sintered microstructure were investigated. The results showed that the fine wood dust waste acted as an effective pore-forming agent. The new bi-layered ceramic tiles showed good technical properties (water absorption=6.16-9.66% and flexural strength=18.10-28.74 MPa). The results also suggested that up to 10 wt% of fine wood dust waste can be valorized in the production of lightweight bi-layered ceramic tiles, which brings together the precepts for sustainable environmental management applications.
Keywords: fine wood dust, waste, bi-layered ceramic tiles, properties, valorization.

INTRODUCTION

Brazil has an expressive wood furniture industry with a wide range of products for residential use, offices, furniture components for restaurants, hospitals, auditoriums, cinemas, hotels, schools, etc. It appears that the use of wood in the manufacture of furniture is significant in the five geographic regions of Brazil: South (88.7%), Midwest (86.1%), Southeast (85.8%), North (81.4%) and Northeast (77.5%) [1]. It is worth mentioning the importance of the impact of the wood furniture industry on the national economy, which generates a lot of wealth with high revenue and is responsible for thousands of direct and indirect jobs. However, in the wake of the wood furniture manufacturing process comes the generation of huge amounts of solid waste.

The solid wastes generated in the wood furniture industry come from several processing steps such as cutting, lamination, drilling, and sanding. These wood wastes are classified based on their morphological characteristics [2, 3] as: i) wood chips (maximum particle size of 50x20 mm, generally from the use of chippers); ii) shavings (particle size >2.5 mm); iii) sawdust (wood particles from sawing, with sizes between 0.5 and 2.5 mm); and iv) fine wood dust (particle size <0.5 mm). The guidelines of the National Policy on Solid Waste (Law 12305/2010 [4]) advocate encouraging the recycling and valorization of wood wastes. When improperly disposed of in the environment, the wood wastes can attract insects such as termites [2]. Among all types of wood wastes from the furniture industry, that classified as fine wood dust (<0.5 mm) is considered the most difficult and complex to be disposed of in an environmentally correct way. For this reason, it is also the one that has received greater rigor from the environmental inspection agencies. It is very thin, light, and easily lifted by the wind. As a result, it can be inhaled by people both indoors and outdoors and cause multiple health problems, including pneumoconiosis, pneumonitis, asthma, bronchitis, allergic rhinitis, and lung cancer [5]. Thus, ecologically correct alternatives for the valorization of fine wood dust are highly desirable and urgent to minimize its impact on the environment and risks to public health.

Nowadays, the ventilated façade is gaining more and more prominence in the construction process of buildings. This is due to several factors, including durability, ease of cleaning and maintenance, aesthetics, thermal comfort, and savings in terms of energy efficiency [6]. Conventional ceramic tiles are widely used in the constructive process of ventilated façades, with special emphasis on that from the BIa group described in the ABNT NBR-ISO 13006:2020 standard [7] (dry-pressed porcelain stoneware tiles) due to their superior technical properties. However, a relevant issue considered in the use of porcelain stoneware tiles concerns their high fired density (~2.38-2.45 g/cm^3) [8], which directly influences the weight and the thermal and acoustic insulation characteristics of the ventilated façade. Due to this demand, a new type of ceramic tile called dense/porous bi-layered ceramic tile has been suggested as a viable option to meet the requirements of weight reduction and adequate thermal and acoustic insulation characteristics [9-11]. Specifically, this new type of ceramic tile proposes to combine a dense top-layer with a porous bottom-layer. It is noteworthy that the porous bottom-layer can be obtained from the introduction of pore-forming agents. In particular, wood waste has already been used as a pore-forming agent in the production of bi-layered ceramic floor tiles [12, 13]. More specifically, forest wood sawdust with granulometry above 0.5 mm was used. However, to the best of our knowledge, the use of wood waste characterized as fine wood dust (with

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a particle size <0.5 mm) from the sanding process in wood furniture factories has not yet been tested. It is known that wood wastes with different particle sizes when decomposed during the firing process, can develop different types of pores, degrees of densification, and thermal conductivity characteristics in the ceramic matrix [14]. In this context, this work investigated the valorization potential of fine wood dust waste from the sanding process of wood furniture as a pore-forming agent in the development of a dense/porous bi-layered ceramic tile.

EXPERIMENTAL

The raw materials used were ceramic tile paste and fine wood dust waste. Table I gives the tile formulations used to prepare the bi-layered ceramic tiles. As seen, the top layer was composed of a traditional ceramic tile paste, hereinafter referred to as GBP0 paste, while the bottom layer was composed of GBP0 paste with up to 10 wt% of fine wood dust waste. The GBP0 paste with particle size <325 mesh (<45 μm) was essentially composed of a mixture of kaolinite, albite, and quartz. Chemically, it was composed of SiO_2 (65.1 wt%), Al_2O_3 (22.5 wt%), Na_2O (4.8 wt%), and other oxides (1.8 wt%), with a loss on ignition of 5.8 wt%. The fine wood dust sample was collected in a wood furniture factory located in the State of Rio de Janeiro, Brazil. It was collected after the sanding step and then passed through a 42-mesh (<0.355 mm) sieve. Fig. 1 shows the morphological aspects of the fine wood dust waste. All ceramic tile formulations (Table I) were prepared by a dry-process [15], and with a moisture content of 7%.

Table I - Formulations used in the preparation of the bi-layered ceramic tiles (wt%).

Formulation	Top layer	Bottom layer	
	GBP0 paste	GBP0 paste	Wood dust waste
GS1	100.0	100.0	0.0
GS2	100.0	97.5	2.5
GS3	100.0	95.0	5.0
GS4	100.0	92.5	7.5
GS5	100.0	90.0	10.0

Differential thermal analysis (DTA) and thermogravimetric analysis (TG) were carried out with a simultaneous thermal analyzer (STA 409E, Netzsch) on the fine wood dust waste and ceramic tile paste (GBP0) using a heating rate of 10 ºC/min under air atmosphere. The bi-layered ceramic tile pieces were prepared into rectangular bars by double uniaxial pressing [10]. Initially, the ceramic tile paste corresponding to the top layer (GBP0 paste) was placed inside a rectangular die (11.5x2.5 cm) and pressed using a hydraulic press (PHP15T, MetalPem) at 8 MPa for 30 s. In sequence, the tile pastes corresponding to the bottom layer (mixtures composed of GBP0 paste and fine wood dust waste, as shown in Table I) were placed inside the die and both layers were pressed simultaneously at 16 MPa for 30 s, resulting in a bi-layered ceramic tile. After that, the green bi-layered tile pieces (five test specimens for each formulation) were dried at 110 ºC for 24 h and fired in a laboratory kiln (FE50RP, Flyever) at 1235 ºC for 4 min, by using a fast-firing cycle (~86 min).

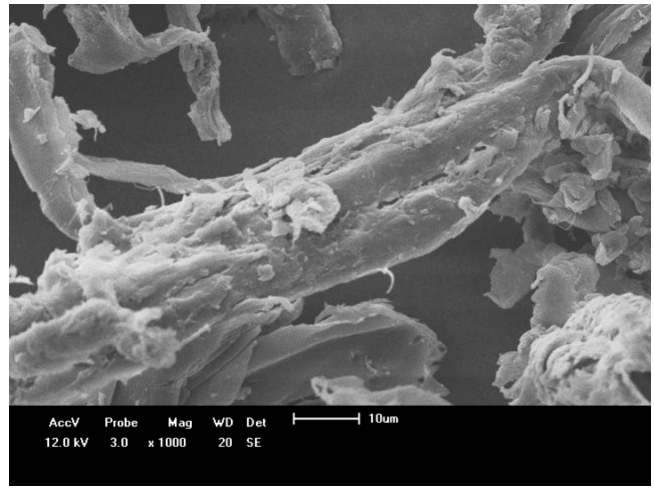
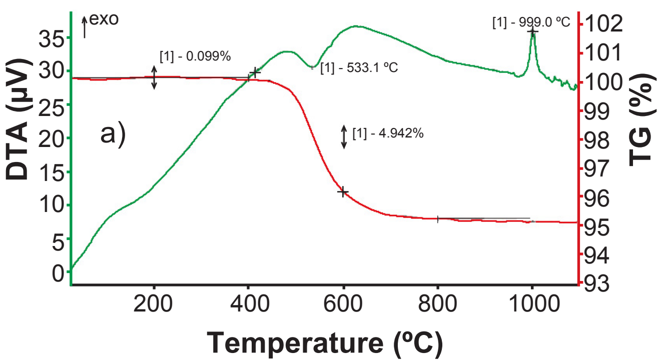


Figure 1: SEM micrograph of the fine wood dust waste.

Linear shrinkage values were determined from the length variation of the rectangular bars according to ASTM C 326-09 standard. The mass loss was determined from the mass measurements of the tile pieces after drying and firing using a balance (±0.01 g). Water absorption, apparent density, and apparent porosity were determined following the procedures described in the ISO 10545-3:2018 standard. The flexural strength was determined by a three-point bending test using a universal testing machine (mod. 5582, Instron) at a loading rate of 0.5 mm/min, according to ISO 10545-4. In the flexural strength test, the rectangular bars were positioned with the porous layer facing downwards. The sintered microstructure of the gold-covered fractured surface was studied using a scanning electron microscope (SSX-550 SEM, Shimadzu) by means of secondary electron images.

RESULTS AND DISCUSSION

In this work, a key issue of great relevance was to determine the efficiency of fine wood dust waste from the sanding process of wood furniture in the processing of lighter bi-layered ceramic tiles. The DTA-TG curves of the GBP0 paste and fine wood dust waste are shown in Fig. 2. It was found that the GBP0 paste showed two endothermic events accompanied by mass losses at ~150 ºC (0.099% due to evolution of physically adsorbed water) and at 533.1 ºC (4.94% due to kaolinite dehydroxylation), as shown in Fig. 2a. An exothermic event at 999.0 °C related to mullite formation has also been identified [16]. Thus, the thermal behavior of the GBP0 paste (fine wood dust-free formulation) was in line with its chemical and mineral composition. The thermal behavior of the fine wood dust waste was characterized by the occurrence of an endothermic event and two exothermic events with significant mass losses (Fig. 2b). The endothermic event at 186.0 ºC with a mass loss of 7.87% was related to the release of physically adsorbed water and volatile decomposition. The exothermic events at 385.3 ºC with a mass loss of 62.27% and at 576.9 ºC with a mass loss of 29.87% were related to the decomposition of organic matter, more specifically the decomposition of hemicellulose, lignin, and cellulose [17]. These results are quite relevant and indicate that the fine wood dust waste was completely destroyed up to ~600 ºC. As a result, it should be expected to act very effectively as a pore-forming agent in the processing of a dense/porous bi-layered ceramic tile.



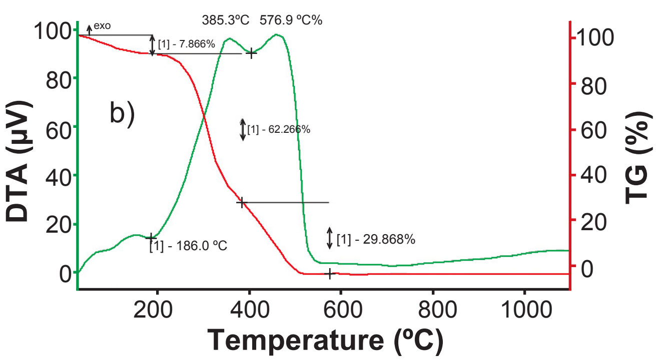


Figure 2: DTA/TG curves of: a) GBP0 paste; and b) fine wood dust waste.

Table II gives the linear shrinkage and bulk density values of the bi-layered ceramic tiles after drying at 110 ºC. An intricate linear shrinkage behavior was observed. A low linear shrinkage value (0.41%) was found for the GS1 formulation (fine wood dust-free formulation). However, the formulations containing fine wood dust waste in the porous bottom layer exhibited a small expansion (between 0.23-0.39%). This expansion effect happened because the fine wood dust waste had the ability to absorb the moisture added in the mass preparation step. Despite this, the low values of linear variation obtained are suitable for the processing of bi-layered ceramic tiles. The results in Table II also showed a decreasing trend in drying density (2.06 to 1.93 g/cm^3) with increasing amount of fine wood dust waste added. This effect was associated with the low wood density value (between 0.561 and 0.904 g/cm^3 [18]), which decreases the global drying density of the bi-layered ceramic tiles.

Table II - Characterization results for the bi-layered ceramic tiles after drying at 110 ºC.

Formulation	Linear shrinkage (%)	Bulk density (g/cm^3)
GS1	0.41±0.03	2.05±0.05
GS2	-0.24±0.04	2.06±0.02
GS3	-0.23±0.05	1.98±0.03
GS4	-0.24±0.03	1.98±0.02
GS5	-0.39±0.07	1.93±0.03

Fig. 3 shows the SEM micrographs of the fractured surfaces of the bi-layered ceramic tiles after firing at 1235 ºC. The effect of the incorporation of fine wood dust waste was quite obvious in the formation of a ceramic tile material with a bi-layered structure. As seen in Fig. 3a, the microstructure of the single dense layer specimen (fine wood dust-free GS1 formulation) was highly densified due to the consistent development of the glassy viscous phase during firing. It was also noted that the thermal destruction of the fine wood dust waste with concomitant release of gas in the bottom layer had little influence on the densification of the top layer of the bi-layered ceramic tiles. However, as shown in Figs. 3b to 3e, the ability of the fine wood dust waste to produce porosity in the bottom layer is evident. The greater the amount of fine wood dust waste added, the greater the amount of open pores of different sizes developed in the bottom layer. Also, apparently, a good interface connection between the top layer (dense layer) and the bottom-layer (porous layer) was obtained. These results confirmed the fine wood dust waste as a relevant pore-forming agent and, as such, it was expected to influence the technical properties of the bi-layered ceramic tiles.

Fig. 4a shows that the bi-layered ceramic tiles presented linear shrinkage values between 8.57% and 9.43%, an acceptable range for the processing of ceramic tile materials. It was noted that the incorporation of the fine wood dust waste caused only a slight variation in the linear shrinkage. However, there was also a trend towards increased linear shrinkage with incorporations above 5 wt% of fine wood dust waste. This trend suggested a higher degree of sinterability of the bi-layered ceramic tiles, which can be explained by the occurrence of simultaneous effects, such as: 1) the fine wood dust waste acted as an auxiliary solid fuel with a high calorific power [14], adding heat to the firing step; and 2) the thermal destruction of fine wood dust waste generated ash rich in fluxing components [19] that contribute to densification.

Fig. 4b displays that the apparent density of the bi-layered ceramic tiles tended to decrease (2.20 to 1.98 g/cm^3) with increasing amounts of fine wood dust waste added. This effect can be explained by the thermal destruction of the fine wood dust waste during firing, resulting in greater mass loss (Fig. 4c) and greater porosity (Fig. 4d) in the bottom layer of the tile material. The results of Fig. 4b also indicated that the fine wood dust waste fulfilled its goal of being an efficient pore-forming agent, which provided a lightweight bi-

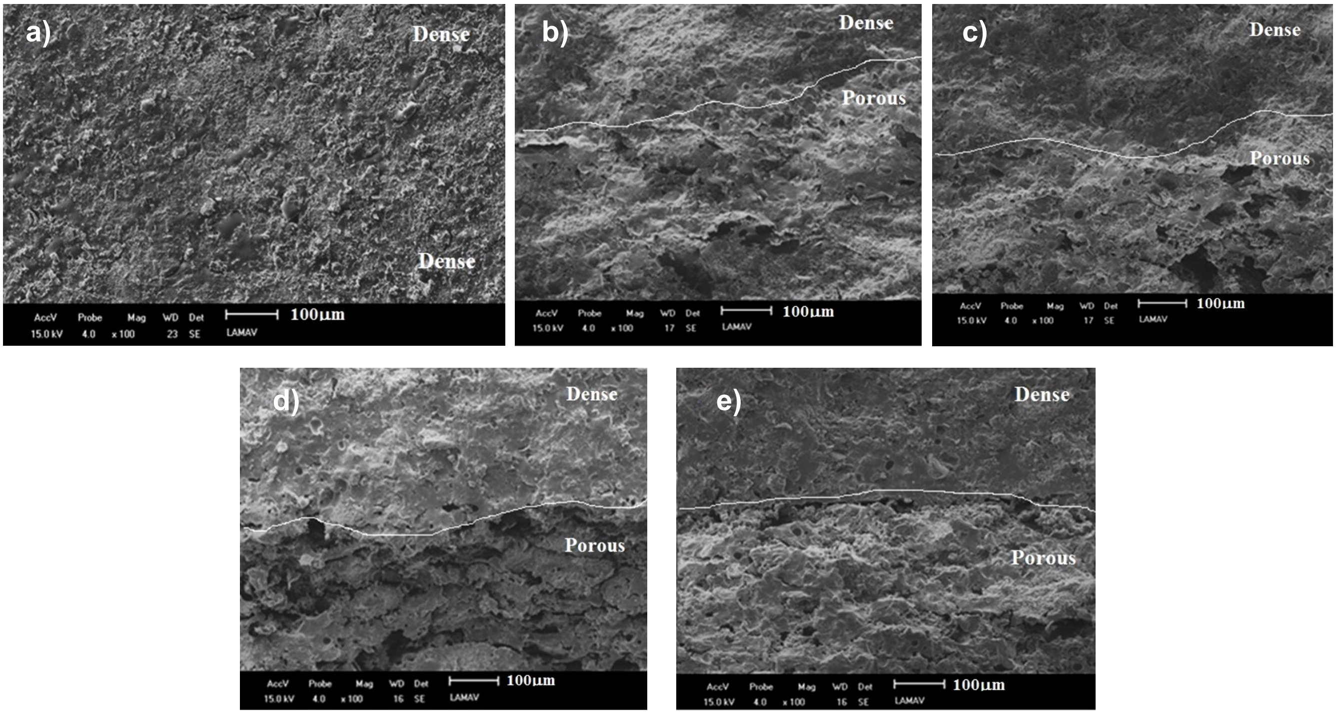


Figure 3: SEM micrographs of the fired bi-layered ceramic tiles: a) GS1; b) GS2; c) GS3; d) GS4; and e) GS5.

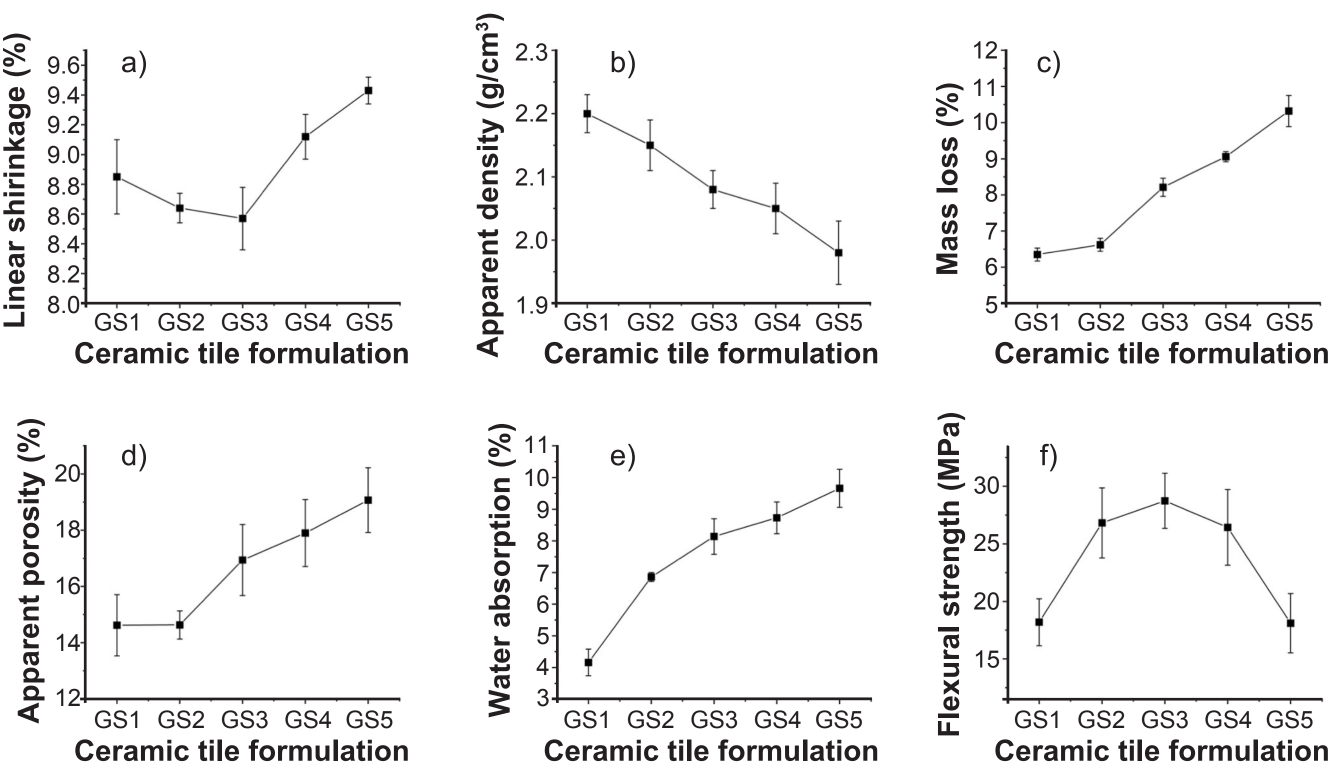


Figure 4: Technical properties of bi-layered ceramic tiles: a) linear shrinkage; b) apparent density; c) mass loss; d) apparent porosity; e) water absorption; and f) flexural strength.

layered ceramic tile. In this scenario, the bi-layered ceramic tiles produced can be up to 10% lighter (GS5 formulation) with potential interest in ventilated façades. Fig. 4e showed a continuous increase in the level of water absorption (i.e., open porosity level) by increasing the amount of fine wood dust waste in the bi-layered ceramic tile formulations. This effect was associated with the destruction of the fine wood dust waste during firing, which created open porosity, particularly in the bottom layer of the newly produced bi-layered ceramic tile. So that the water absorption values (Fig. 4e) were in tune with those obtained from the fired microstructure (Fig. 3), apparent density (Fig. 4b), mass loss (Fig. 4c), and apparent porosity (Fig. 4d).

Fig. 4f shows an intricate behavior for the flexural strength of the fired bi-layered ceramic tiles. There was a trend towards an increase in flexural strength with the incorporation of up to 5 wt% of fine wood dust waste. This finding was mainly due to the greater sinterability of the bi-layered ceramic tiles. New additions of fine wood dust waste above 5 wt%, however, tended to decrease flexural strength. In this case, the larger pore volume and larger pore sizes developed in the fired tile structure prevailed over the sinterability. This finding was in line with the microstructural evolution, shown in Fig. 3.

The development of the bi-layered ceramic tiles is recent and, therefore, there is no standard that serves as a basis for establishing a comparison. For this reason, this work sought to classify the bi-layered ceramic tiles produced using the conventional classification generally used for single-layer ceramic tiles. Thus, the bi-layered ceramic tiles produced using fine wood dust waste were tentatively classified according to water absorption (WA) and manufacturing method (dry-pressing) according to the ABNT NBR-ISO 13006:2020 standard [7]. The reference single-layer ceramic tile (GS1 formulation) met the requirements of the BIIa group (3%<WA≤6%). Nevertheless, the bi-layered ceramic tiles incorporated with fine wood dust waste (GS2, GS3, GS4, and GS5 formulations) met the requirements of the group BIIb (6%<WA≤10%). Therefore, the fine wood dust waste incorporated tended to modify the technical characteristics of the ceramic tile, making it lighter and more favorable for situations that require thermal comfort, such as in ventilated façades. In this context, the valorization of fine wood dust waste for the production of light bi-layered ceramic tiles can be a viable option for the practical application of this pollutant solid waste.

CONCLUSIONS

The feasibility of using fine wood dust waste in the production of dense/porous bi-layered ceramic tiles was evaluated. According to the obtained results, fine wood dust waste played a crucial role in the creation of open pores in the bottom layer of the bi-layered ceramic tiles. Due to this, the fired microstructure, densification, and technical properties of the bi-layered ceramic tiles were also influenced. It was found that the incorporation of fine wood dust waste makes it possible to reduce the fired density by up to 10% with positive repercussions for potential application in ventilated façades. For the conditions used in this work, the dense/porous bi-layered ceramic tiles produced with up to 10 wt% of fine wood dust met the requirements of group BIIb (6%<WA≤10%, ABNT NBR-ISO 13006:2020 standard). Thus, the fine wood dust waste can be valorized as an effective porogenic agent for the processing of dense/porous bi-layered ceramic tiles. In addition, this simple approach can find a very useful and sustainable destination for fine wood dust waste, which can provide multiple beneficial impacts for the wood furniture industry and society.

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