Conjecturas

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Mortar intended for the production of cementitious slabs: use of waste green foundry sand and polymeric fibers

Argamassa destinada à produção de placas cimentícias: uso de resíduo de areia verde da fundição e fibras poliméricas

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ABSTRACT

The development of cementitious cover slabs with replacement of natural sand (NS) by waste green foundry sand (WGFS) and with addition of polyester fibers was the main objective of this work. Different percentages of replacement of NS by WGFS (0, 25, 50, 75 and 100%), different cements (CP-V ARI and CP-II Z 32) and addition of polyester fibers (0% and 0.6%) were employed as factors in the experimental design. The results showed that the apparent specific mass decreased when the percentage of aggregate replacement was increased, however, the air void and water absorption of the composite increased with replacement. The highest compressive strengths were obtained for the mortars made entirely with NS, which reached 20.4 MPa and 12.9 MPa for cements CP-V ARI and CP-II Z, respectively. The addition of fibers showed no evidence of significant influence on the properties of prismatic specimens, but the fibers were significantly influential on the properties of cementitious plates. Evaluating the results, it is observed that the total replacement of NS by WGFS, in cementitious cover slabs, is not recommended, because the mechanical strengths reduce around 60% when compared to the reference material.

Keywords: Foundry green sand residue; Cementitious slab; Polymeric fibers; Properties.

RESUMO

O desenvolvimento de placas cimentícias de revestimento com substituição da areia natural (NS) por resíduo de areia verde de fundição (WGFS) e com adição de fibras de poliéster foi o principal objetivo do presente trabalho. Diferentes porcentagens de substituição da NS por WGFS, diferentes cimentos e adição de fibras de poliéster foram empregados como fatores no projeto experimental. Os resultados mostraram que a massa específica aparente diminuiu quando a porcentagem de substituição do agregado foi aumentada, porém, o índice de vazios e a absorção de água do compósito aumentaram com a substituição. As maiores resistências à compressão foram obtidas para as argamassas confeccionadas totalmente com NS, que atingiram 20,4 MPa e 12,9 MPa para os cimentos CP-V ARI e CP-II Z, respectivamente. A adição de fibras não apresentou evidências de influência sobre as propriedades corpos de prova prismáticos, porém as fibras foram significativamente influentes nas propriedades das placas cimentícias. Observa-se que a substituição total da NS por WGFS, em placas cimentícias de revestimento, não é recomendada, pois as resistências mecânicas reduzem em torno de 60% quando comparadas com o material de referência.

Palavras-chave: Resíduo de areia verde da fundição; Placa cimentícia; Fibras polimérica; Propriedades.

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INTRODUCTION

The manufacturing process known as foundry is used to transform materials in a liquid state, mainly metals, into parts with complex shapes. This process is one of the main generators of industrial waste, with discarded foundry sand being the waste generated in larger quantities. According to the Brazilian Foundry Association (ABIFA, 2022), the production of castings in Brazil in the year 2022 reached 2.348 million tons, and for each ton of castings generated, one ton of waste sand is produced.

The casting processes can be varied, but the molding method using green sand is the most used because it is simple and less expensive than the others (ARMANGE et al., 2005). All the sand used in the casting process is reused until it reaches a point of inefficiency, that is, the green sand loses its physical-chemical bonding properties and can no longer be reused. Thus, the sand is removed from the system and becomes considered a waste, known as discarded foundry sand (DFS), becoming a problem for the industry, which needs to give a correct destination for this waste (ANDRADE, 2018).

Foundry industries need to dispose of this waste in controlled landfills. According to Rodrigues (2018), this process ends up generating high costs and, if not performed, contributes to the worsening of environmental problems, since it pollutes the soil and, especially, surface and underground water. In addition, the extraction of natural sand for industrial use also generates significant environmental impacts (CARNIN, 2010). Thus, from the environmental and economic point of view, the reuse of foundry sand that needs disposal strengthens the idea that new destinations should be found for this material.

In general, DFS is classified by NBR 10004 (ABNT, 2004) as Class II A waste, i.e., a non-hazardous and non-inert waste. Waste with this classification has the potential to be reused in civil construction.

One of the solutions that has been investigated is the use of this waste as a raw material in cementitious matrices. Several studies show that this is a viable solution, for example, in the production of concrete (MASTELLA et al., 2014; KHATIB et al., 2013; KAUR et al., 2012) and mortar (OLIVEIRA, 2014; MOON et al., 2005; MONOSI et al., 2010; CASALI et al., 2018), having the advantage of decreasing the production costs of this type of product (ARMANGE, 2005). Depending on the composition, DFS waste can replace the binder (cement) and/or the aggregate (sand).

One possible use of the green foundry sand waste is in the development of cementitious plates, which can be used for internal or external closure of buildings, or as decorative elements in civil construction. Some works show the feasibility of adding waste in the formulation of mortars for making cementitious slabs, such as Moraes Filho (2019), who replaced Portland cement with sugarcane bagasse ash in cementitious slabs, verifying that, according to the guidelines of ABNT NBR 15498/2016, the materials produced with the concentration of the residue between 12% and 40% meet the requested parameters for the tests of tensile strength in simple bending, water absorption and permeability, enabling the application of the cementitious plate for both internal and external sealing. On the other hand, Arruda Filho (2019) produced cementitious plates reinforced with sisal and verified increased toughness and post-cracking strength gain, concluding that these plates show potential to be used as structural, semi-structural or sealing elements.

Despite these existing studies, there is still no consensus on the use of foundry green sand waste in the development of cementitious plates. In this context, the present work aims to study the technical feasibility of developing a mortar for making a cementitious coating plate, with the addition of foundry green sand, replacing the natural sand. Also, the effect of adding polyester fibers was investigated on the properties of cementitious plates.

MATERIALS AND METHODS

In this work, cementitious slabs were produced for vertical cladding with the use of foundry green sand waste (WGFS), replacing natural sand (NS), and with or without the addition of polyester fibers. The execution of the work was divided into different stages, which can be seen in the infographic of Figure 1.

Initially, the collection, preparation, and characterization of the materials were performed, then the specimens were made, and, finally, the characterizations of the specimens were performed according to different tests.

Aggregates

The aggregates used were natural sand (NS), which was purchased in Passo Fundo/RS and extracted in the region of Santa Maria - RS. This sand was considered as reference sand. The waste green foundry sand (WGFS) discarded by the foundry sector was acquired from a company in the northern region of RS. The polyester fibers were purchased commercially. Figure 2(c-e) shows the aggregates used.

Figure 1 – Aggregates: (a) natural sand (b) green foundry sand waste and (c) polyester fibers.

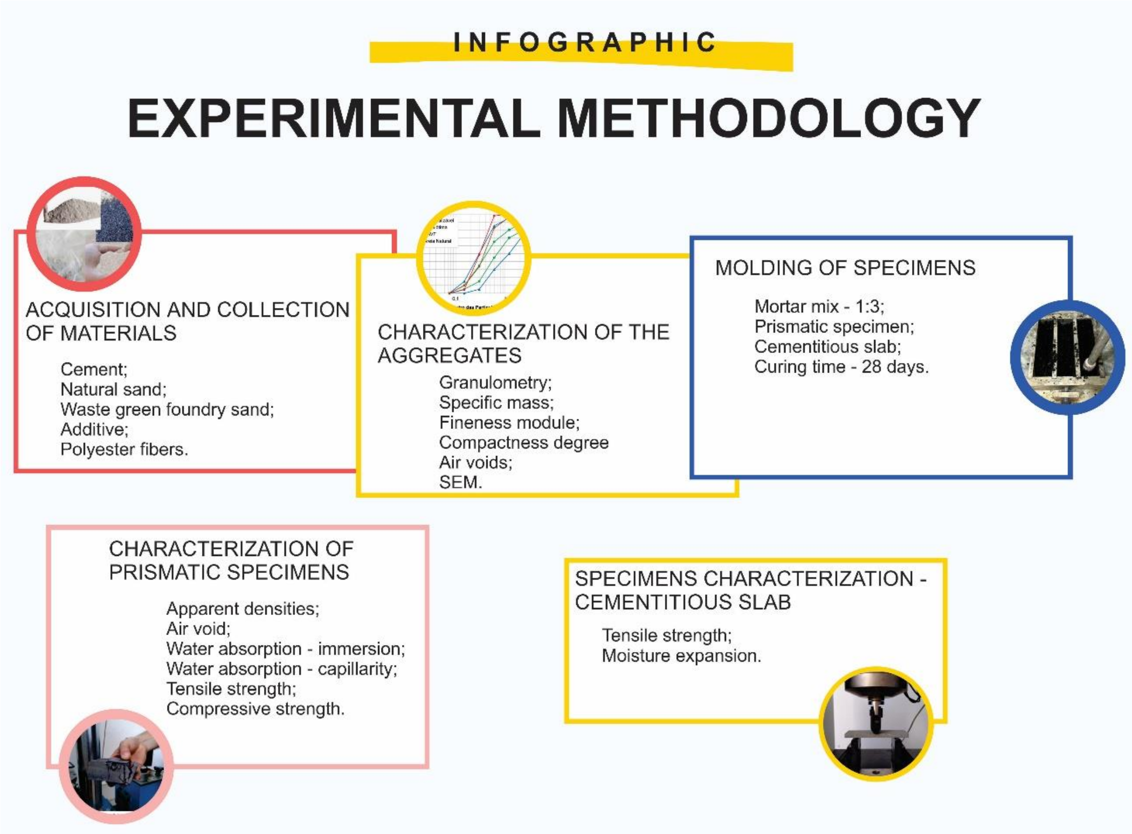
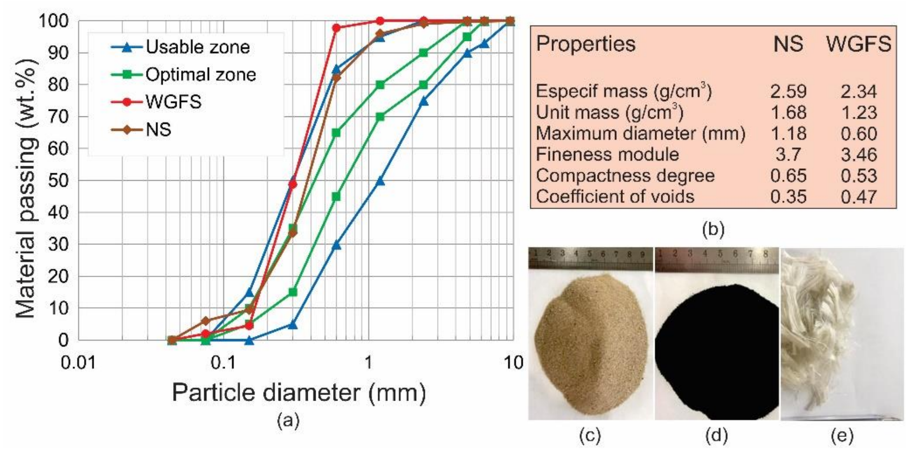


Figure 2 – Aggregates: (a) natural sand (b) green foundry sand waste and (c) polyester fibers.



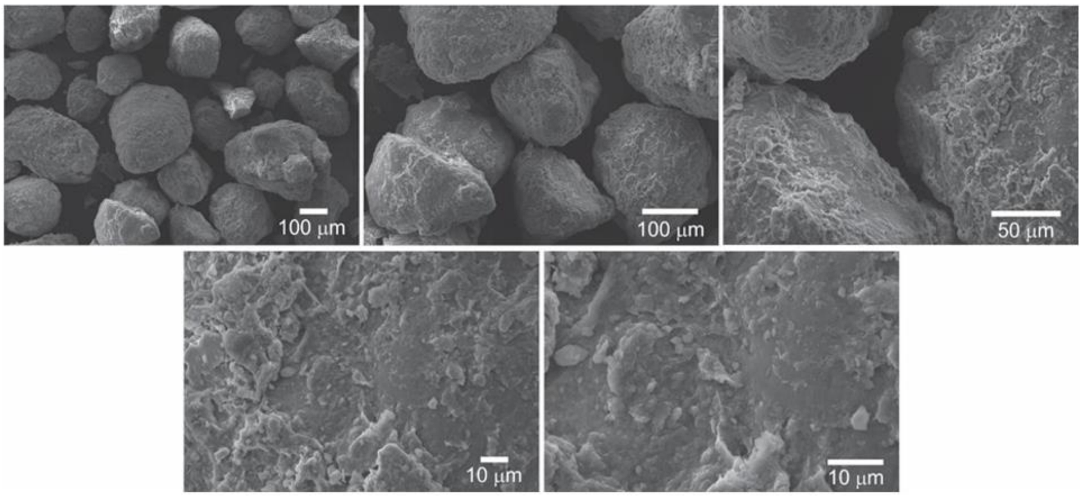
The WGFS went through a sieve processing to avoid some impurities and dimensional variations of the grains (for example, pieces of the mold, clods/clumps, metals from the remains/shavings of the manufactured parts). Thus, the WGFS passing through a 1.18 mm sieve was used.

Figure 2(a) shows the particle size distribution curves of the NS and the WGFS, as well as the optimal and usable zones, according to NBR NM 248 (ABNT 2003). Tests were also performed for particle size analysis (particle size curve and fineness modulus), following the recommendations of NBR NM 248 (ABNT, 2003), specific and apparent mass, according to NBR NM 52 (ABNT, 2003), degree of compactness and void ratio, in accordance with NBR NM 45 (ABNT 2006). The results are presented in Figure 2(b).

The sands are classified, according to NBR NM 248 (ABNT, 2003), as fine sands. It can be seen that the particle size distribution of WGFS is more uniform, which implies its higher voids coefficient, while the NS has grains better distributed, i.e., of different sizes, leading to lower voids.

Figure 3 shows images of the WGFS, which were made by scanning electron microscope (SEM). The presence of rounded grains is observed, which confirms the possibility of generating more voids. It is also observed that the grains are coated and, as reported by Monosi (2013), this coating consists of bentonite, clay and a "fine carbon powder".

Figure 3 – Scanning electron microscopy of WGFS.



Binders

Two types of binders were used in this research, Portland cement CP-II Z 32 and Portland cement CP-V ARI. The cement CP-II Z 32 was chosen because it is the most used for making mortars in general, it has an addition of fly ash, which brings greater impermeability and durability. The Portland cement CP-V ARI was chosen for being a purer cement and for reaching the maximum strengths in a shorter curing time. The characteristics of the cements used are shown in Table 1 and were obtained from the manufacturer.

Table 1 – Physical and chemical properties of the cements (Itambé, 2019).

Type of cement	Physical Properties									
	Setting time		Blaine cm^2/g	#200 %	#325 %	HE[1] %	D[2] g/cm^3	Compressive strength		
	Initial h:min	Last h:min						3 days MPa	7 days MPa	28 days MPa
CP-II Z	03:21	04:00	3.6221	2.73	12.29	27.5	3.96	26.5± 1.2	32.7 ± 1.2	41.6 ± 1.0
CP-V ARI	03:29	04:16	4.411	0.07	0.33	29.9	3.09	39.5± 1.2	45.3 ± 1.2	53.8 ± 1.0

Type of cement	Chemical properties									
	Al_2O_3 %	SiO_2 %	Fe_2O_3 %	CaO %	MgO %	SO_3 %	LOI[3] . %	Free CaO %	I.R.[4] %	A.E[5] %
CP-II Z	6.87	22.59	3.10	53.20	3.94	2.77	5.01	0.80	12.31	0.8
CP-V ARI	4.46	19.28	3.0	61.86	2.59	2.95	3.62	0.97	0.81	0

[1] HE – Hot expansion; [2] D - Density; [3] LOI – Loss on ignition; [4] I.R. -Insoluble Residue; [5] A.E. - Alkaline Equivalent.

Additive

To improve the workability of the mortar and reduce the water/cement (w/c) ratio, according to what Speck (2014) reports, the plasticizer additive MC-TechniFlow 580 was added, which was used in the amount of 0.6% of the cement mass. This amount is in accordance with the manufacturer's specification (Table 2) and, also, with the amounts used by other studies found in the literature, such as the work of Speck (2014), who did his study on cementitious slabs produced with the addition of glass fibers and wire mesh, and Azevedo (2018), who produced cementitious slabs using primary sludge, which is a waste product from the pulp paper industry.

Table 2 – Additive specifications (MC-Bauchemie, 2019).

Features	Value	Remarks
Density	1.10 kg/L	NBR 10908:2008
Recommended Dosage	0.2% a 2.0%	About the weight of the cement

Fibers

Polyester fibers are widely used in concrete and mortar aiming to improve strength characteristics and reduce pathological manifestations, especially in the appearance of cracks. The use of fibers is justified because it is a study of cementitious plates, which are artifacts subject to greater cracking. Table 3 shows the characteristics of polyester fibers.

Table 3 – Characteristics of polyester fibers (FibraFix, 2019).

Properties	Results
Density (g/cm^3)	1.64
Stem length (mm)	20
Stem diameter (micron)	25
Melting point (°C)	235
Autoignition point (°C)	650
Relative thermal conductivity to air	5.0
Water Resistance	Non-Tackable Hydrophobic
Resistance to acids	Good
Alkali resistance	Very good
Water absorption (%)	< 0.4
Tensile strength (MPa)	0.3 – 0.5
Young's Modulus (MPa)	2500

METHODS

Fabrication of the specimens

To make the specimens, four percentages of replacement of NS by WGFS were evaluated: 0%, 25%, 50%, 75% and 100%. In addition, the type of cement was varied (CP-V ARI and CP-II Z 32) and the addition or not of polyester fibers (amount of 0.6% by mass, in relation to the total mass of the mixture). For all mixes, the water/cement ratio (0.45) and the additive amount (0.6%, relative to the cement mass) were kept constant. In this work, the same mix adopted by Azevedo (2018) of 1:3 (cement:sand/waste) in cement mass was employed. According to the author, this is the most commonly used mix in the manufacture of coating mortars. The quantities for each material specimen are exposed in the experimental matrix of Table 4.

The mixture was prepared according to NBR 13276 (ABNT, 2005). First, the cement, natural sand and waste were manually homogenized (dry mix) and then water with the plasticizer additive was included (liquid mix) then a mechanical mortar mixer was used and mixing continued until complete homogenization was observed.

After making the mortars, prismatic specimens were produced, according to NBR 13279 (ABNT, 2005), with dimensions 40x40x160 mm, in two layers, compacted with 30 blows in each of the two layers.

Table 4 – Experimental matrix.

Order	TC	C (kg)	NS (kg)	WGFS (kg)	% Replacement	Fibers	A/C
1	CP-V ARI	0,75	2,25	0	0	No Addition	0,45
2	CP-V ARI	0,75	2,25	0	0	With addition	0,45

3	CP-V ARI	0,75	1,69	0,56	25	No Addition	0,45
4	CP-V ARI	0,75	1,69	0,56	25	With addition	0,45
5	CP-V ARI	0,75	1,125	1,125	50	No Addition	0,45
6	CP-V ARI	0,75	1,125	1,125	50	With addition	0,45
7	CP-V ARI	0,75	0,56	1,69	75	No Addition	0,45
8	CP-V ARI	0,75	0,56	1,69	75	With addition	0,45
9	CP-V ARI	0,75	0	2,25	100	No Addition	0,45
10	CP-V ARI	0,75	0	2,25	100	With addition	0,45
11	CP-II Z	0,75	2,25	0	0	No Addition	0,45
12	CP-II Z	0,75	2,25	0	0	With addition	0,45
13	CP-II Z	0,75	1,69	0,56	25	No Addition	0,45
14	CP-II Z	0,75	1,69	0,56	25	With addition	0,45
15	CP-II Z	0,75	1,125	1,125	50	No Addition	0,45
16	CP-II Z	0,75	1,125	1,125	50	With addition	0,45
17	CP-II Z	0,75	0,56	1,69	75	No Addition	0,45
18	CP-II Z	0,75	0,56	1,69	75	With addition	0,45
19	CP-II Z	0,75	0	2,25	100	No Addition	0,45
20	CP-II Z	0,75	0	2,25	100	With addition	0,45

TC - Type of cement; C - Amount of cement; NS - Amount of natural sand; WGFS – Waste foundry green sand; A/C water-cement ratio.

Cementitious slabs were also made. To perform the moldings, the same procedure adopted for the prismatic specimens was followed, however, the specimens were built with dimensions of 150x50x10 mm, defined from the study of Azevedo (2018). According to the author, these dimensions are demonstrative for execution on a laboratory scale, but their results can be perfectly extrapolated to larger sizes.

The demolding of the specimens and the cementitious plates occurred 24 hours after molding, when they were sent for curing at room temperature of approximately 25 °C for 28 days.

Characterization of mortars in the hardened state

The characterization of the mortars in hardened state was performed through tests performed on prismatic specimens in triplicate. These were characterized for bulk density, air void and water absorption by capillarity. In addition, their mechanical properties were evaluated through flexural tensile strength and compressive strength tests.

The analysis of specific mass and void ratio was performed in accordance with the NBR 9778 (ABNT, 2009), along with the mortar water absorption test. The capillary water absorption test was performed according to the recommendations of NBR 15259 (ABNT, 2005). The capillarity coefficient evaluates the ability of water to penetrate and travel through the pores of the mortar, which in this case must intercommunicate, being a reference to durability parameters, which can be evaluated in slabs. According to

Bardella et al. (2005), water absorption and permeability in slabs is one of the main means of transporting aggressive agents into the cementitious mass.

The tests for flexural tensile strength and compressive strength were performed according to NBR 13279 (ABNT, 2005). For flexural tensile strength, the prismatic specimen was subjected to the "three-point bending" test in an EMIC DL 10000 press, with a loading capacity of 10000 kN. After this load application, the specimens are separated in half and then submitted to the compressive strength test by an EMIC PC 200C press, with an application capacity of 200 kN.

Characterization of cementitious slabs

To characterize the developed cementitious slabs, tensile flexural strength and moisture expansion tests were performed.

For the mechanical resistance to bending, NBR 15498 (ABNT, 2016) was followed. This test is known as "bending in thirds", where loading is applied in two symmetrical sections. The equipment used to perform the test was the DL 10000 press, with capacity for 10000 kN of force.

The expansion by humidity (EPU) was performed according to the recommendations of NBR 13818 (1997). According to Oliveira (2004), this expansion is known as hygroscopic expansion and occurs when there is an increase in the size of a ceramic or cement plate with the presence of moisture. The same author also reports that UPS values greater than 0.6 mm/m can significantly contribute to slab detachment problems, because the expansion of the slabs after their laying can generate stresses that impair the stability of the entire coating.

RESULTS AND DISCUSSIONS

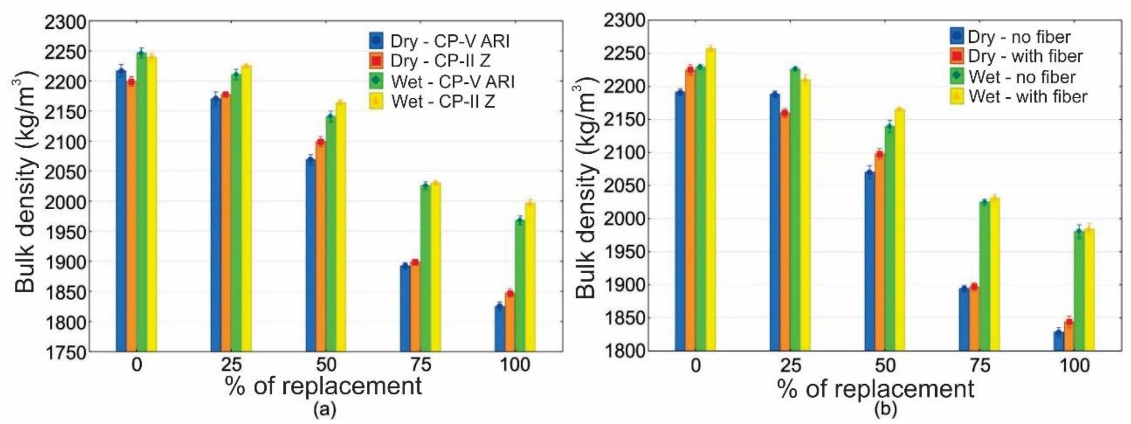
The results are described for mortars in the hardened state (prismatic specimens) and cementitious cover slabs.

Characterization of mortar in the hardened state

Apparent Density

The results of the bulk density (dry and saturated) can be seen in Figure 4. It can be seen that the densities decrease when the percentage of aggregate replacement increases. This is due to the fact that the specific mass of the waste (2.34 g/cm³) is lower than that of natural sand (2.59 g/cm³). This result was also observed by other authors, such as Rufino and Galdino (2015), who analyzed mortars with the introduction of foundry waste.

Figure 4 – Dry and saturated bulk densities as a function of the percent substitution for (a) the two types of cement and (b) fiber addition or not.



For the CP-V ARI cement, the mixture with 100% substitution had a decrease of 18% compared to the reference mixture in the dry density values, and in the saturated density, this decrease was 12.5%.

For the CP-II Z cement, this difference was smaller; in dry density it decreased by only 16% while in saturated density the decrease was 11% comparing the 100% mixture with the reference mixture.

Among the factors evaluated, through the analysis of variance (ANOVA), according to Tables 5 and 6, the only factor that had significant influence, with 95% or more reliability, was the percentage of waste substitution. Furthermore, it is observed that there is no evidence of the influence of different types of cement and fiber addition on densities.

Table 5 – ANOVA for dry apparent specific mass.

Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	1403	1	1403	3,6	0,0649	No
Replacement %	1326684	4	331671	840,2	0,0000	Yes
Addition of fibers	1578	1	1578	4,0	0,0506	No
Error	20921	53	395			

Table 6 – ANOVA for saturated specific mass.

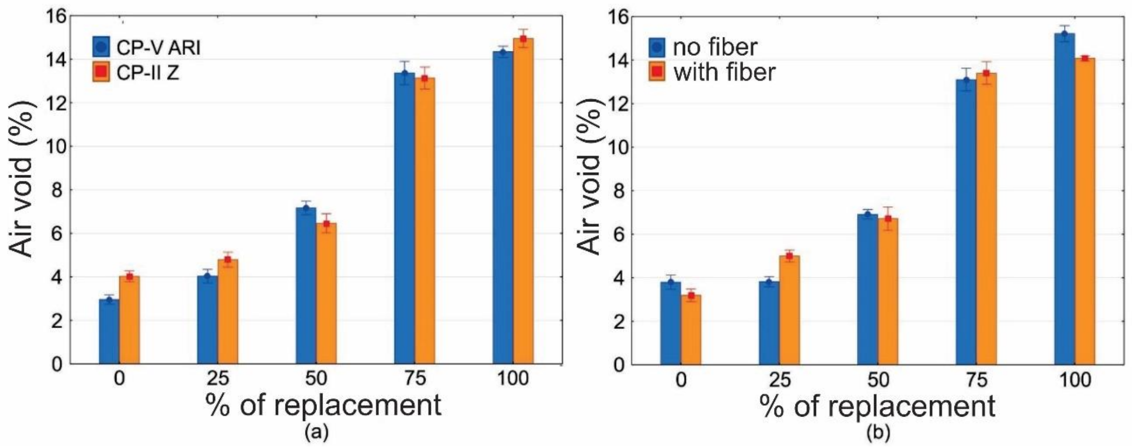
Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	2406	1	2406	8,8	0,0044	No
Replacement %	635945	4	158986	582,2	0,0000	Yes

Addition of fibers	1312	1	1312	4,8	0,0327	No
Error	14472	53	273			

Air void

The air void as a function of the mortar replacement percentage are presented in the graphs in Figure 5.

Figure 5 – Air void as a function of % replacement for (a) the two types of cement and (b) addition or non-addition of fibers.



It can be observed that by increasing the percentage of substitution of natural aggregate for WGFS, the voids in the composites increase. This may be associated with the presence of charcoal and bentonite that are superficially adhered to the grains of the residue. According to Casali et al. (2018), because they are considered organic matter and cause the increase of the transition zone between the paste and the aggregate, their presence causes the increase of voids and formation of large crystals of Ca(OH)2 . The voids are directly linked to the results of bulk density, water absorption and mechanical strength, because the more voids, the lower mass will have the composite and lower mechanical strength, but higher water absorption.

It can be seen that the maximum value of air void reached was 15% and occurred with total replacement of NS by WGFS. This result, when compared with the study of Rufino and Galdino (2015), in which they observed voids ratios of 14% with only 30% of waste substitution, is a promising value, because fewer voids can provide greater mechanical strength.

The mixture with 100% of waste and cement CP-V ARI, showed an increase in voids of 79% compared to the reference mixture. With the cement CP-II Z, this increase was 73.3%.

Table 7 shows the ANOVA results for the voids content test. Also, the only factor that significantly influences the void ratio was the percentage of replacement of natural aggregate by waste.

Table 7 – ANOVA for the voids index.

Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	1,344	1	1,344	1,468	0,2310	No
Replacement %	1259,956	4	314,989	343,965	0,0000	Yes
Addition of fibers	0,123	1	0,123	0,134	0,7158	No
Error	48,535	53	0,916			

Water absorption by immersion

The results of water absorption by immersion as a function of the percentage of replacement of natural sand by WGFS can be seen in the graphs in Figure 6. According to the increase in the percentage of waste substitution, there is also an increase in water absorption values, which was already expected, because the voids content is directly related to water absorption, the more voids in the composite, the greater will be its water absorption.

It can also be seen that there was an increase of more than 75% in water absorption when comparing the mixtures with 100% substitution with the reference mixtures. Speck (2014), who made cementitious slabs with the addition of glass and polypropylene mesh and fibers, found absorptions around 3%, similar to that found in the present research, with replacement of approximately 50% of NS by WGFS.

In Table 8, it can be seen that the variable that influenced water absorption was also the percentage of substitution of WGFS. As for the other factors, there is no evidence of influence on this variable.

Figure 6 – Water absorption by immersion as a function of % replacement for (a) the two types of cement and (b) fiber addition.

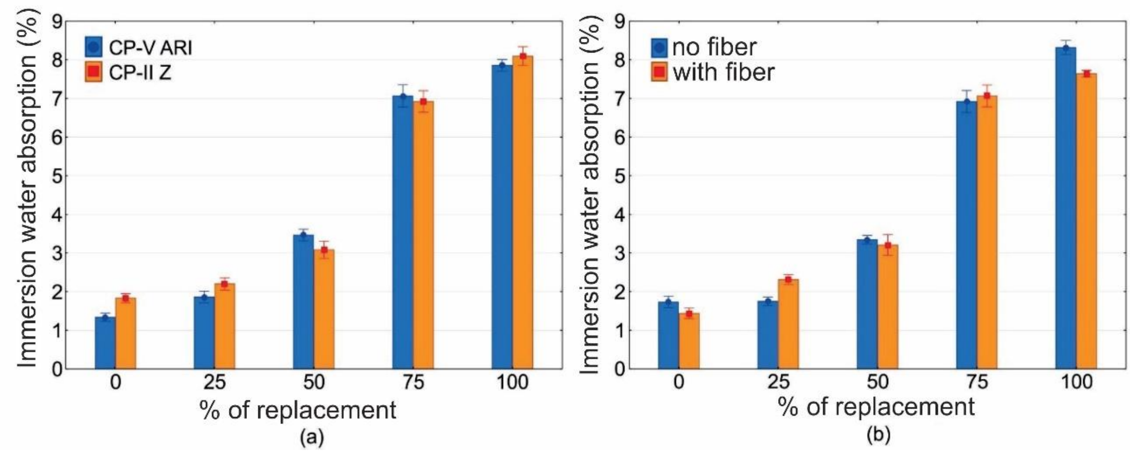


Table 8 – ANOVA for water absorption by immersion.

Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	0,178	1	0,178	0,716	0,4012	No
% Replacement	411,950	4	102,988	414,959	0,0000	Yes
Addition of fibers	0,094	1	0,094	0,377	0,5418	No
Error	13,154	53	0,248			

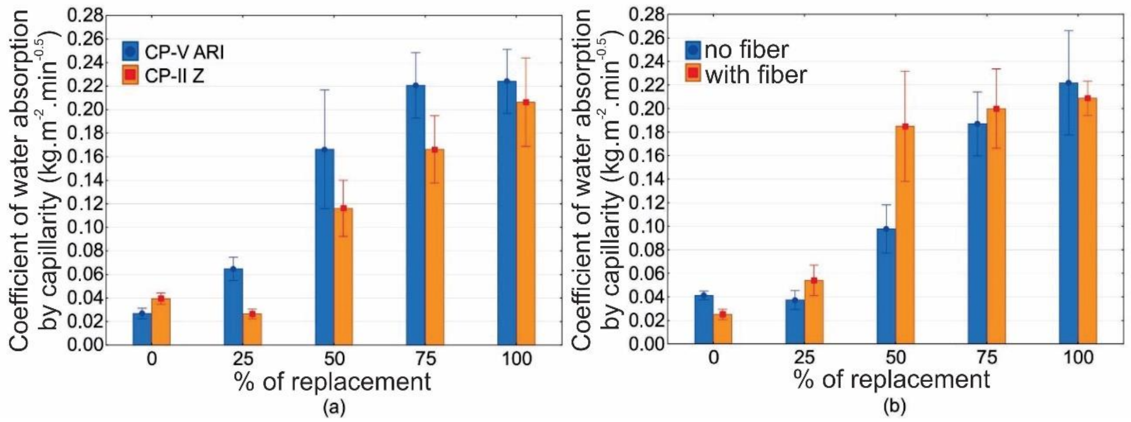
Water absorption by capillarity

The absorption by capillarity is very impactful on the durability of composites because it promotes water ingress generating an internal flow, which can have high pH due to the alkaline products generated by the paste. Besides the external CO2 flow, which can harm the existing reinforcing materials (KARATAS et al, 2017). Thus, it is believed that water absorption through capillary pores plays a key role in the durability of mortars, because the higher the absorption value, the greater the problems caused by water in the internal part of the composite.

Figure 7 shows the graphs of the capillary water absorption coefficient as a function of the replacement percentages for the different types of cement and fiber addition.

The evaluation of capillarity absorption is done by the coefficient, where the higher its value, the greater the connection of the internal pores. The highest capillarity absorption coefficient was detected in the highest substitution contents of the sands. The maximum value found was 0.226 kg.m-2.min-0,5 . This result, when classified according to the standard NBR 13281 (ABNT, 2005), fits in class C1 (class with lower capillarity coefficients).

Figure 7 – Water absorption by capillarity as a function of % replacement for (a) the two types of cement and (b) addition or non-addition of fiber.



As expected, with the increase in the incorporation of waste, there was also an increase in the absorption coefficient, which was more evident in the cement CP-V ARI, compared to CP-II Z. This behavior, possibly, is due to the composition of the types of cement, being CP-V ARI more pure and with higher heat of hydration, which can cause micro cracks that connect the pores. Moreover, with the addition of fibers, in most cases, there was an increase in the value of the coefficient, because the fibers provide greater intercommunicability between the pores, according to Azevedo (2018).

Table 9 shows the ANOVA results for the capillary absorption values, pointing out the significance only of the percentage of substitution.

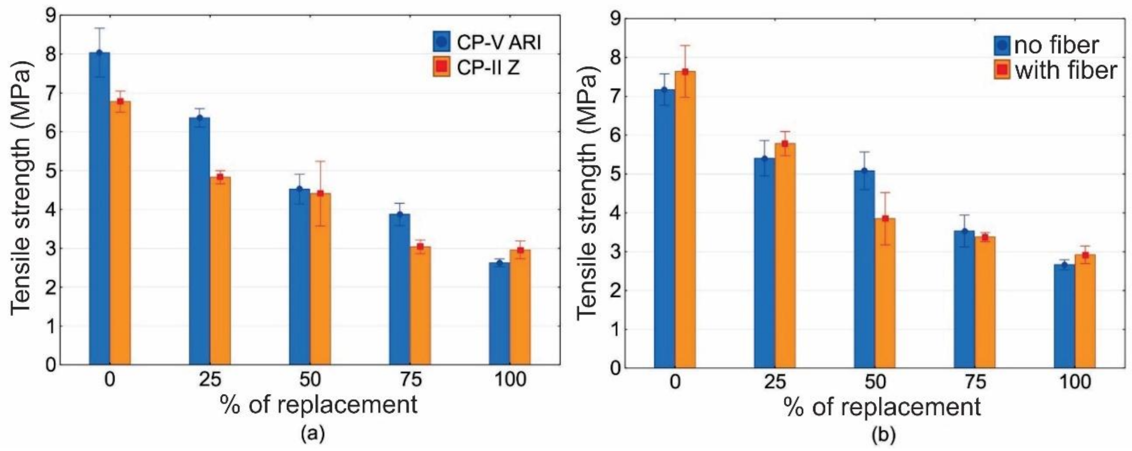
Table 9 – ANOVA for the capillary absorption coefficient.

Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	0,013109	1	0,013109	3,2341	0,0778	No
Replacement %	0,333785	4	0,083446	20,5867	0,0000	Yes
Addition of fibers	0,004627	1	0,004627	1,1414	0,2901	No
Error	0,214830	53	0,004053			

Bending tensile strength

Figure 8 shows the results of flexural tensile strength as a function of the percentage of replacement for the different types of cement and addition or not of polyester fiber. The results show that the flexural strength decreases with increasing percentage of replacement of NS by WGFS.

Figure 8 – Flexural tensile strength as a function of % replacement for (a) the two types of cement and (b) fiber addition or not.



According to the classification of this parameter by NBR 13281 (ABNT, 2005), the mortar fits from class R5 even with total aggregate replacement, which indicates that this mortar is among the best classifications. It can also be observed that for the cement CP-V ARI, with 100% of residue use, there was a decrease of 67.3% in the values of tensile strength when compared to the reference mixture. For the CPII cement, this decrease was 56.3%.

These results are in line with other existing works in the literature where the use of the waste decreased the strength of cementitious products (NAIK, 2003; GURDEEP et al., 2012; SIDDIQUE R., KADRI EL-HADJ, 2011; GUNEY Y. et al., 2010). In two of their studies, Monosi et al. (2010) and Monosi (2013), report that the reduction in mechanical strength is due to the presence of binder in the foundry sand, composed of a fine carbon and clay powder, which can cause problems in the bonds between the cement paste and the aggregates.

In the ANOVA performed for the results of flexural tensile strength, shown in Table 10, it is observed that the significant factors for the flexural tensile strength of prismatic mortar specimens were the percentage of substitution and the type of cement. Regarding the use of fibers, there was no statistical evidence that the fibers influence significantly on the flexural strength.

Table 10 – ANOVA for flexural tensile strength.

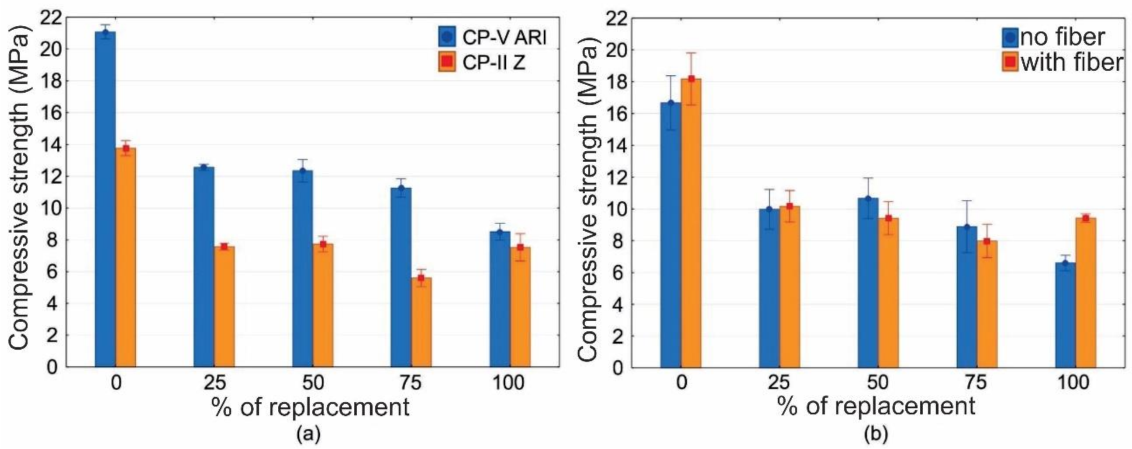
Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	6,956	1	6,956	6,810	0,0117	Yes
% Replacement	160,298	4	40,074	39,231	0,0000	Yes

Addition of fibers	0,051	1	0,051	0,050	0,8239	No
Error	54,139	53	1,021			

Compression strength

The results of compressive strength as a function of replacement percentages can be seen in the graphs in Figure 9.

Figure 9 – Compressive strength as a function of % replacement for (a) the two types of cement and (b) fiber addition.



The highest compressive strength was obtained for the mortars made entirely with NS, which reached the maximum value of 21.09 MPa for cement CP-V ARI and 13.89 MPa for cement CP-II Z. The loss of strength of the mixture with 100% replacement in relation to that with 0% WGFS was around 40% for cement CP-V ARI and 54% for cement CP-II Z. The addition of fibers had no influence on the compressive strength. This can be proven by the analysis of variance in Table 11.

The reduction in compressive strength values with the increase in the percentage of substitution of NS by WGFS may have occurred due to the increase in the air void and the lack of adhesion between the cement paste and the WGFS.

Table 11 – ANOVA for compressive strength.

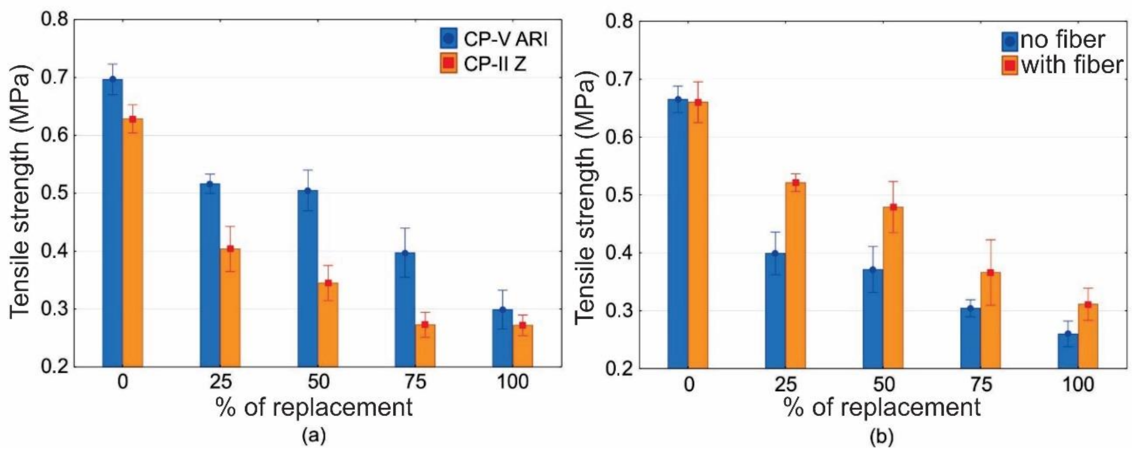
Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	332,982	1	332,982	119,078	0,0000	Yes
Replacement %	700,428	4	175,107	62,620	0,0000	Yes
Addition of fibers	3,396	1	3,396	1,215	0,2754	No
Error	148,205	53	2,796			

Characterization of the cementitious slabs

Flexural tensile strength

Figure 10 shows the flexural tensile strength results performed on the cementitious slabs, which were made with different percentages of substitution of NS by WGFS, with different types of cements, and with the addition or not of fibers.

Figure 10 – Flexural tensile strength of cementitious slabs as a function of the % substitution for (a) the two types of cement and (b) addition or non-addition of fiber.



The flexural tensile strength for the slabs decreases with the increase in the percentage of aggregate substitution. This result is in agreement with the results obtained in the tests of prismatic mortar specimens. It is also observed that the slabs produced with CP-V ARI resulted in higher values than those produced with CP-II Z, for the same reasons cited in the results found for mortar flexural tensile strength.

A reduction of 57.2% in tensile strength was observed for both cements with 100% use of waste. Moreover, the addition of fibers generated an increase in flexural tensile strength for all percentages of replacement tested, but for the reference mixture, there was no variation in the means of strength.

All factors showed significant influence for the flexural tensile strength for the cementitious plates. This can be confirmed by the ANOVA in Table 12.

Table 12 – ANOVA for flexural strength in cementitious slabs.

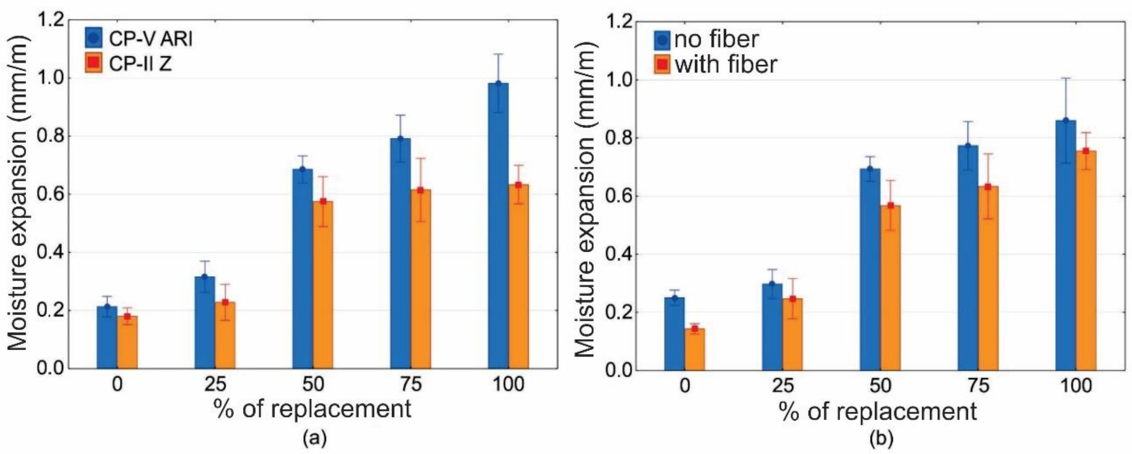
Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	0,14503	1	0,14503	33,077	0,0000	Yes
Replacement %	1,01848	4	0,25462	58,070	0,0000	Yes

Addition of fibers	0,06849	1	0,06849	15,619	0,0002	Yes
Error	0,23239	53	0,00438			

Expansion by humidity

The moisture expansion (ME) results are presented in the graphs in Figure 11.

Figure 11 – Moisture expansion as a function of % replacement for (a) the two types of cement and (b) fiber addition or not.



The expansion by moisture increases with the increase of aggregate replacement by waste, for both cements and for the slabs with fiber addition. The results show that up to 50% of aggregate replacement by waste for cement CP-II Z meets the expansion value required by NBR 13818 (ABNT, 1997), which is 0.6 mm/m for cementitious slabs. For the cement CP-V ARI only 25% of substitution met this requirement.

The same occurs when analyzing the addition of fibers to the composite, percentages of up to 50% fit the standard specification.

The increase observed for the cement CP-V ARI and 100% replacement was 78.6% compared to the reference mixture. For cement CP-II Z, this increase was approximately 71.5%.

Thus, all factors were significant in the results, as can be seen in Table 13.

Table 13 – ANOVA for moisture expansion.

Factor	Sum of squares	Degree of freedom	Mean Square	F value	P value	Significant
Type of cement	0,34353	1	0,34353	11,8250	0,001146	Yes
Replacement %	3,53336	4	0,88334	30,4066	0,000000	Yes
Addition of fibers	0,16748	1	0,16748	5,7651	0,019888	Yes

CONCLUSIONS

Regarding the physical characteristics, the WGFS and NS were classified as 'fine sand', according to NBR NM 248 (ABNT, 2003), but both have some differences. The WGFS presented uniform particle size distribution, with higher content of fines, which made it go beyond the usable zone. This implied a higher coefficient of voids. In addition, the residue has a lower specific mass when compared to natural sand. The NS has better distributed grains, i.e., of different sizes and thus lower void coefficient, consequently lower porosity, which increases the mechanical strength of the piece.

It is concluded that the apparent specific mass decreases when the percentage of aggregate replacement increases, thus, when the material is totally replaced it presents much lower specific masses. With the increase in the percentage of aggregate replacement by WGFS, the voids in the composites also increase. The voids are directly linked to the results of specific mass, absorption and strength, because the more voids, the lower mass will have the composite, but lower mechanical strength and higher water absorption, of the capillary vessels. It was also concluded that the mechanical strength results obtained decreased according to the increase in the percentage of substitution of RAVF. Even so, the results obtained from the mortar produced with and without waste, meet the requirements requested by NBR 13281 (ABNT, 2005).

The mechanical strengths of the slabs decreased with the increase in the percentage of aggregate replacement. Moreover, according to NBR 15498 (ABNT, 2016), the results found are not satisfactory because the values of flexural tensile strength of the slabs cannot be less than 70% of the minimum value required by the standard.

The addition of fibers in the composite caused an increase in strength when compared to those without fibers, since the fiber acts in improving the flexural tensile strength, even with the increase of the percentages of replacement in the mixtures. The polyester fiber used may not be so representative in the mechanical strength, however, its greatest influence is in combating pathologies that may occur in cementitious plates, such as cracks and fissures that can be caused by moisture expansion, as seen in the study by Sousa et al. (2019).

Thus, it is concluded that the replacement of natural sand by green foundry sand proved to be very effective for the production of mortars, but when these were applied in cementitious plates the results were not promising. Thus, it can be seen that the type of reinforcement is of paramount importance in the mechanical strength of the cementitious plate.

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