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Pervious concrete with waste foundry sand: mechanical and hydraulic properties

Concreto permeável com areia descartada de fundição: propriedades mecânicas e hidráulicas

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ABSTRACT

One of the main challenges of the metallurgical industry is the management of the principal waste generated in the production of castings, which is the waste foundry sand (WFS). Potential solutions include the use of WFS in civil construction due to its mineral origin and the high volume available to meet possible demand. This study analyzed the influence of WFS on the mechanical and hydraulic properties of pervious concrete paving blocks. The experimental stage involved mixtures with 0% (reference) and 100% replacement of quartz sand (QS) by WFS, in concrete with consumption of 350 kg/m^3 and 450 kg/m^3 of Portland cement. Cylindrical specimens, pavers, and pervious concrete slabs were submitted to water absorption, compressive strength, and determination of the permeability coefficient (k) tests. Analysis for physicochemical characterization of leachate samples of the studied concretes was also carried out. After the statistical analysis of the results, it was possible to conclude that the WFS did not change the mechanical (Rc; Rt) and hydraulic (k; absorption) properties of pervious concrete mixes (WFS1; WFS2) when compared to the reference mixes (QS1; QS2). The changes in the results of the physicochemical parameters are related to the higher consumption of Portland cement from mix 2, increasing hardness, total solids, and alkalinity.
Keywords: Pervious pavement. Industrial waste. Compressive strength. Porosity. Sustainable material.

RESUMO

Um dos principais desafios da indústria metalúrgica é o gerenciamento do principal resíduo gerado na produção de peças fundidas, que é a areia descartada de fundição (ADF). As soluções potenciais incluem a utilização da ADF na construção civil devido à sua origem mineral e ao grande volume disponível para atender a possível demanda. Este estudo analisou a influência da ADF nas propriedades mecânicas e hidráulicas de blocos de pavimentação de concreto permeável. A etapa experimental envolveu misturas com 0% (referência) e 100% de substituição da areia quartzosa (AQ) por ADF, em concretos com consumo de 350 kg/m^3 e 450 kg/m^3 de cimento Portland. Corpos-de-prova cilíndricos, pavers e placas de concreto permeável foram submetidos aos ensaios de absorção de água, resistência à compressão e determinação do coeficiente de permeabilidade (k). Também foram realizadas análises para caracterização físico-química de amostras de lixiviado dos concretos estudados. Após a análise estatística dos resultados, foi possível concluir que a ADF não alterou as propriedades mecânicas (Rc; Rt) e hidráulicas (k; absorção) dos traços de concreto permeável (ADF1; ADF2), quando comparados aos traços referência (AQ1; AQ2). As alterações nos resultados dos parâmetros físico-químicos estão relacionadas ao maior consumo de cimento Portland do traço 2, resultando no aumento da dureza, sólidos totais e alcalinidade.
Palavras-chave: Pavimento permeável. Resíduos industriais. Resistência à compressão. Porosidade. Material sustentável.

1. INTRODUCTION

In general, industrial plants are considered waste generators resulting from processes that transform natural resources into consumer goods. In this context, one of the most relevant issues is the use of solid waste com-

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pulsorily generated by the production sectors to preserve natural resources and reduce environmental liabilities.

A promising type of solid waste is the waste foundry sand (WFS), generated and discarded by the foundry industry during the molding processes of metal parts. Global annual production of WFS is around 62.64 million tons [1], with annual disposal of 3 million tons in Brazil [2]. According to DYER *et al.* [3], WFS represents the largest volume of environmental liabilities of the foundry industry (steel, metal, automobile) also involving economic impacts (segregation, storage, and final disposal in own or third-party landfills).

This waste can be obtained from several casting methods, which will depend on the complexity of the part to be molded [3]. WFS that does not have organic material in their composition are classified as 'green sand,' mainly comprised of silica sand (85 to 95%), bentonite (4 to 10%) used as a binder, pulverized coal (2 to 10%) as an additive, to improve the surface finish of the metal part, and water (2 to 5%) to obtain plasticity. This molding process is still the most frequently used in Brazil as it is a fast low-cost method, therefore, producing the highest amount of WFS.

Potential applications of WFS include its use as an aggregate in geotechnical applications and cementitious materials due to the available volume and physical-mechanical properties of this waste [4-8]. MASTELLA *et al.* [7] investigated the use of WFS in the manufacture of cement artifacts (paving blocks) containing different rates of WFS (up to 75%). The results showed compressive strength values of the concrete blocks made with WFS were statistically equal to those obtained from the reference (0% WFS), besides the meet the requirements of the Brazilian standard [9].

To increase the sustainability of cementitious materials with WFS, we have the option of pervious concrete, as it is considered sustainable for allowing larger permeable areas and drainage of rainwater [10]. One of the main applications of pervious concrete is the manufacture of paving blocks, which offer easy installation and economic advantages [11]. However, when proposing the use of WFS in this type of concrete, studies are required to define the permeability and mechanical properties [12-16].

According to a report issued by the American Concrete Institute, the compressive strength of pervious concrete should range from 3.5 to 28 MPa, with void values between 15% and 35% [17]. In Brazil, the requirements for this type of concrete establishes that the pervious concrete paving blocks must have a minimum compressive strength of 20 MPa and a permeability coefficient (k) above 10^{-3}m/s [18].

The properties of the pervious concrete mixture depend on maintaining an optimal relation between permeability/porosity and mechanical properties [13, 16]. HIDAYAH *et al.* [15] and CHANDRAPPA and BILLIGIRI [16] studied the influence of aggregates (coarse and fine) in the properties of pervious concrete on paving blocks. They concluded the size of coarse aggregates affects the strength (4 to 12%). The results also showed that the permeability coefficients presenting a relation with porosity, but non-linear adjustment.

XU *et al.* [19] investigated the properties of porous concrete modified with fine aggregate and conclude that the fine aggregate can improve the compressive strength and durability of pervious concrete. The study also demonstrates that the use of fine aggregate enhances the conjoint point between the aggregates in porous concrete.

Another important factor that must be studied for pervious concrete with WFS is the risk of soil and water contamination. ANDRADE *et al.* [20] evaluated, through leaching tests, the use of WFS in partial replacement to natural fine aggregate in the production of concretes. The results indicated that there was no significant change in the pH and electric conductivity of leaching samples obtained in concrete with WFS when compare with reference concrete.

Based on these considerations, this study aimed to develop the hydraulic and mechanical properties of pervious concrete with WFS in paving blocks.

2. MATERIALS AND METHODS

In this study, Portland cement CP V-ARI was used, with compressive strength at day 7 of 24 MPa [21]. Two types of fine aggregate were used: conventional sand (quartz sand), classified as fine sand (zone 2), according to [22] and obtained in the region of Limeira, São Paulo. The WFS samples were obtained from the foundry process called "green sand" which does not use phenolic resins as a binder and provided Foundry Company located in the South region of Brazil. As for the environmental characterization test [23], the ADF sample was classified as a non-hazardous and non-inert waste (Class II A), according to the solubilization test [23] and presented in Table 1.

Table 1: Solubilization Test in the sample WFS

PARAMETER	UNIT	LQ[a]	RESULTS	WHO[b]	MAV[c]
pH WFS	-	2 - 13	7.6	6.5 – 9.2	2 – 12.5
Solubilized aluminum	[mg/L]	0.01	11.6	0.2	0.2
Solubilized iron	[mg/L]	0.01	4.22	0.3	0.3
Solubilized sodium	[mg/L]	0.5	97.9	200	200
Solubilized sulfate	[mg/L]	10	179	200	250
Final pH of the solubilized	-	0 - 14	7.1	-	-
Final pH of the leachate	-	-	5.2	-	-

[a] LQ = Limit of Quantification; [b] Limits established by World Health Organization [24]; [c] Maximum allowed value [23]

Regarding the solubilized extract (Table 1), the amounts of aluminum oxide (Al) and iron oxide (Fe) showed concentrations higher than the standard for the solubilization test, characterizing the waste as not inert in these tests. Thus, as the waste is contaminated with metals that can be solubilized in water and reach groundwater in industrial landfills, generating environmental impact. These results can be modified when the residue is incorporated into cementitious matrices, as it can be encapsulated by the hydration elements of the cement Portland. BITTENCOURT [25] and CASALI *et al.* [26] submitted WFS samples to the same test, also verifying higher concentrations of the same elements regarding the maximum limits allowed by [23].

Figure 1 and Table 2 show the granulometric curves of the aggregates, determined according to standard [27]. Coarse aggregate was characterized as gravel 0, with particle sizes between 4.8 mm and 9.5 mm, from a basaltic rock. Granulometric curves (Figure 1) and physical characteristics (Table 2) of WFS indicate that this material can be used as fine aggregate. MACCAGNAN *et al.* [28] used a WFS sample with a similar fineness modulus (FM) to concrete (1.51 and 1.73, respectively). However, when comparing the FM of the WFS and QS samples, there is a difference of 26%, which can modify the fresh and hardened properties of the pervious concrete.

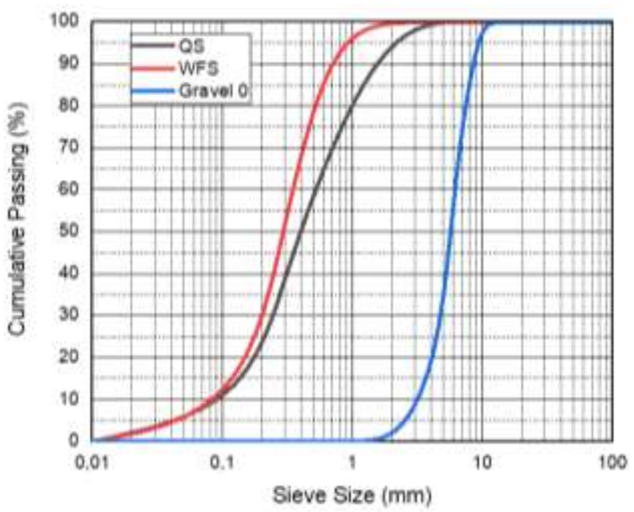


Figure 1: Granulometric curves of quartz sand, WFS and gravel 0.

Table 2. Physical characterization of samples of quartz sand (QS), gravel and waste foundry sand (WFS).

PHYSICAL CHARACTERISTICS	WFS	QS	GRAVEL
Unit mass (g/cm^3) [29]	1.43	1.50	1.56
Specific mass (g/cm^3) [30]	2.50	2.62	3.00
Fineness modulus (FM)	1.51	2.04	5.78
Maximum dimension (mm)	1.2	2.4	9.5
Classification	Very fine sand	Fine sand	Gravel 0

The X-RAY fluorescence analysis (XRF) was performed using a Zetium XRF spectrometer (PANalytical). Loss by fire was conducted at 1020°C for two hours. Table 3 shows the chemical composition of WFS used in this study as compared to other studies found in the literature.

Table 3: Chemical composition of WFS used in this study and WFS reported by different authors obtained by XRF.

REFERENCE	MgO	Al_2O_3	SiO_2	Cr_2O_3	SO_3	K_2O	CaO	Fe_2O_3	LOI*
This study	0.33	2.71	90.00	1.25	0.18	0.45	0.23	2.37	1.93
SIDDIQUE *et al.* [4]	1.95	6.32	78.81	-	0.05	-	1.88	4.83	2.15
BASAR and DEVECI AKSOY [31]	1.97	10.41	81.85	0.02	0.84	0.49	1.21	1.81	6.93
MASTELLA *et al.* [7]	0.06	0.45	96.12	-	-	-	0.08	0.37	0.47
FERREIRA *et al.* [32]	-	18.38	71.46	0.73	2.35	0.20	1.02	2.25	-
GÜRKAN *et al.* [33]	2.30	5.30	79.60	-	-	0.60	1.40	3.10	-
BILAL *et al.* [34]	0.21	4.63	88.50	-	0.03	0.01	0.90	0.83	4.37

*LOI: Loss on ignition

The main chemical components present in the WFS sample include SiO_2 (90%) and Al_2O_3 (2.71%), which are also predominant in QS [31]. Some compounds such as Fe_2O_3 (2.37%) and Cr_2O_3 (1.25%), present in the WFS sample, are the result of the melting process, which were also found by other authors [32].

2.1 Concrete mixtures

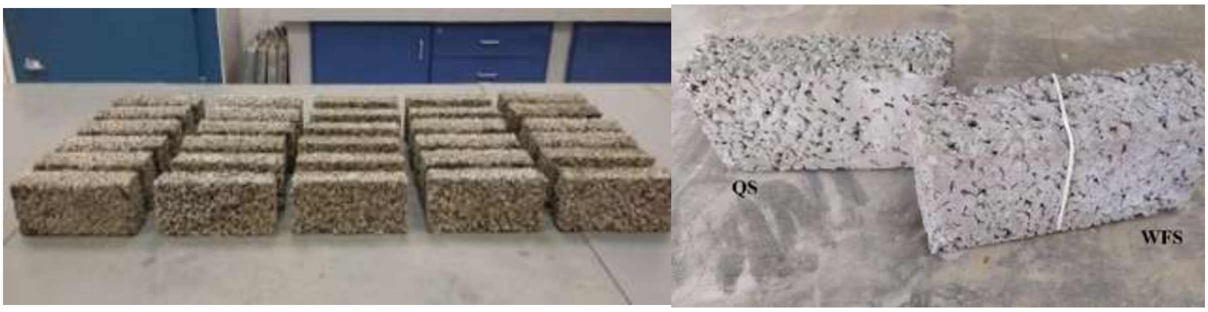
The two mixtures to produce pervious concrete to paving blocks were defined according to the proportions reported by KIA *et al.* [35], differing only in the content of Portland cement (355 kg/m^3 and 450 kg/m^3 of concrete). Table 4 shows the proportions of the materials used in the study (cement consumption method). The difference between the values of the specific mass of quartz sand (2.62 g/cm^3) and WFS (2.50 g/cm^3) resulted in only 0.5 kg of fine aggregate more for pervious concrete with WFS each m^3 of permeable concrete.

Table 4: Proportion of pervious concrete mixtures produced in this study and reference study.

	UNIT	KIA *et al.* [35]	MIX 1		MIX 2	
			QS	WFS	QS	WFS
Coarse aggregate	kg/m^3	1100 to 2800	2135.9	2132.6	1937.9	1932.2
Fine aggregate (sand)	kg/m^3	0 to 100	85.4	85.3	77.5	77.4
Cement	kg/m^3	150 to 700	356.0	355.4	452.2	451.5
Water/cement ratio	-	0.2 to 0.5	0.4	0.4	0.4	0.4
Aggregate/cement ratio	-	2 to 12	6.24	6.24	4.45	4.45
Fine/coarse aggregate ratio	-	0 to 0.07	0.04	0.04	0.04	0.04
Materials proportion			(PC:S:CA:W/C) (1:0.24 : 6 : 0.4)		(PC:S:CA:W/C) (1: 0.17: 4.28: 0.4)	

PC: Cement Portland; S: sand (QS or WFS); CA: Coarse Aggregate; w/c: water/cement ratio.

Thirty specimens were molded into pervious concrete paving blocks, in rectangular molds (0.20 x 0.10 x 0.06 m), for each mix and type of fine aggregate used (with and without WFS) according to [36]. Therefore, this stage involved the molding of 120 pervious concrete paving blocks (Figures 2a and 2b).



(a) (b)

Figure 2: Specimens of pervious concrete paving blocks; (a) after demolding; (b) Pervious paving blocks with QS and WFS after 28 days.

The standards were considered for the determination of compressive strength, water absorption by immersion, void index and specific mass were [37, 38], respectively. The standard NBR 9781 [9] was used to verify the hydraulic, and mechanical specifications of concrete paving blocks.

2.2 Physico-chemical tests of the solubilized of the samples pervious concrete

The analyzes were performed with the solubilized of the QS and WFS samples pervious concrete of both mixtures obtained according to [39]. The procedure spanned the solubilized agitation for 24 h by Tumbler equipment. After this period, was obtained physico-chemical parameters of leachate samples, w to establish possible qualitative differences between the solubilized of the quartz sand and WFS, using the methodology established by APHA [40].

2.3 Permeability of the pervious concrete

2.3.1 Permeability test according to ACI 522R-10

The permeability coefficient (k) is related to the hydraulic properties of the materials, i.e., to the numerical representation of how easy a material allows fluid to flow through its voids. The k values for pervious concrete mixtures were obtained according to the recommendations of the [17], adapted by [41]. This standard proposes the use of a variable load permeameter (Figure 3), where the pervious concrete sample is placed into a PVC pipe located just below a 1- meter-high water column.

The test begins by opening a valve in the part of the PVC pipe below the specimen, measuring the time (seconds) required for total percolation of water through pervious concrete. This procedure was performed in triplicate for each of the three specimens of each mix, resulting in x tests. The value of the permeability coefficient (k) is obtained through Equation 1.

$$k = \frac{A_1 . L}{A_2 . t} log\left(\frac{h_1}{h_2}\right) \quad (1)$$

where: k is the permeability coefficient (cm/s), A_1 is the cross section of the pipe (cm²), L is the length of the cylindrical sample (cm), A_2 is the area of its cross section (cm²), t is the time elapsed between the flow of h_1 to h_2 (s), h_1 and h_2 are the initial and final levels of water (cm).

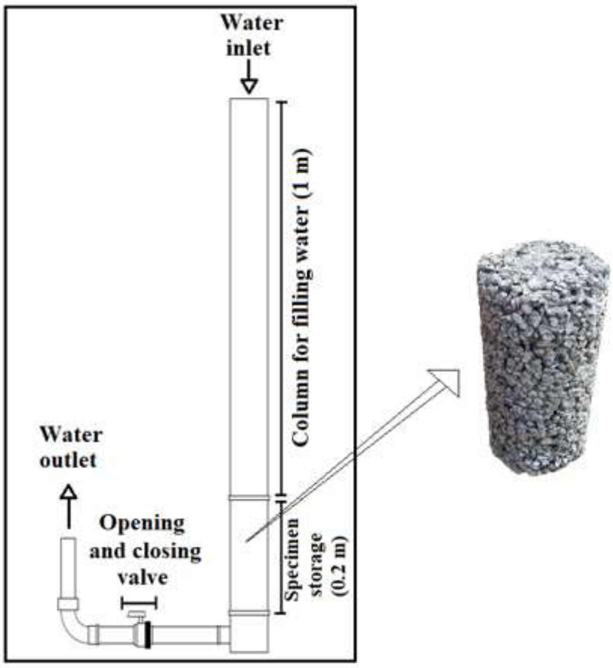


Figure 3: Schematic representation of the variable load permeameter.

2.3.2 Permeability test according to NBR 16416:2015

The methodology for the permeability test using paving blocks was adapted according to ABNT NBR 16416 [18]. The equipment used was an infiltration ring with a diameter of (300 ± 10) mm and a minimum height of 50 mm, as indicated in the standard, two internal reference lines were made at 10 mm and 15 mm in relation to the lower face of the ring. A scale, a container with a minimum volume of 20 L, a stopwatch, caulk, and water were also used. The first step was to clean the pervious concrete paving blocks and then allocate them in a plate format (400 x 300 x 60) mm. After that, the infiltration ring was positioned and with the caulk, the sealing of the ring edge on the plate surface was performed, Figure 4a. At the end of the procedure, pre-wetting was performed on the plate, with water being constantly poured, making the water remain between the markings made on the ring, the time is timed, as shown in Figure 4b.

(a) (b)

Figure 4: (a) Representative scheme and configuration of the materials used in the permeability test; (b) Pre-wetting of permeable concrete plate.

The time was reached when the water was on the surface of the paving blocks. From this date, was calculated the permeability coefficient (k), following Equation 2.

$$k = \frac{C.m}{(d^2.t)} \tag{2}$$

where: k is the permeability coefficient (mm/h); m is the infiltrated water mass (kg); d is the internal diameter of the infiltration cylinder (mm); t is the time required for all percolating water (s); C is the SI unit conversion factor (4583666000). An analysis of variance (ANOVA) was performed to assess the results of the compressive strength and permeability coefficient of the material. ANOVA aims to compare the average sample population, and thus identify whether these averages differ significantly between them. Tukey's test was applied in case of rejection of the null hypothesis. The statistical analysis was performed with R software, version 3.6.3.

3. RESULTS AND DISCUSSION

3.1 Physical properties of hardened pervious concrete

The parameters about physical properties in the hardened state are essential to understand pervious concrete performance [37]. The Table 5 shows the results of the physical characteristics of two concretes this study.

Table 5: Results of physical tests with hardened concrete according to NBR 9778 [38].

PROPERTIES	MIX 1		MIX 2	
	QS	WFS	QS	WFS
Water absorption by medium immersion (%)	6.60	5.85	6.47	6.57
Average void index (%)	15.43	15.35	14.92	14.87
Average specific mass of the dry sample (g/cm³)	2.34	2.36	2.30	2.26
Average specific mass of the saturated sample (g/cm³)	2.49	2.49	2.45	2.41
Actual specific mass (g/cm³)	2.77	2.73	2.71	2.66

According to ACI 522R [17], pervious concrete is a material that must have a void index of 15 to 25% of its total volume. When comparing the values of this study with the ACI range, is possible to conclude that WFS did not change the characteristics of the pervious concrete. The small reduction of the void index (1.5%), obtain for mix 2 with WFS, can be justified by the higher content Portland cement. This occurred due to the refinement of the pores present in the transition zone (between aggregates and paste). In relation to the other physical parameters (specific mass, water absorption), no significant variation was observed, in both cement consumption and use of WFS.

3.2 Compressive strength

Table 6 shows the results of compressive strength obtained for each pervious concrete mix and curing age (7 and 28 days). Also, contain the descriptive statistical analysis (SD; CV; maximum and minimum $f_{c;}$ f_{ck}). According to [18], the pervious concrete f_{ck} must be >/= 20 MPa (for pedestrian traffic) is 20 MPa, which was obtained for Mix 2.

Table 6: Results of the compressive strength test.

		f_C (MPa)	$f_{C\ min.}$(MPa)	$f_{C\ max.}$(MPa)	SD (MPa)	CV (%)	f_{ck} (MPa)
Mix 1	**QS (7 days)**	14.85	13.8	16.0	0.73	4.95	14.2
	WFS (7 days)	17.03	14.4	19.7	1.94	11.39	15.2
	QS (28 days)	15.53	13.8	17.6	1.40	9.01	14.2
	WFS (28 days)	19.95	14.7	21.9	2.65	13.31	17.5
Mix 2	**QS (7 days)**	29.96	28.2	31.3	1.01	3.38	29.0
	WFS (7 days)	31.58	26.6	34.8	2.93	9.26	28.9
	QS (28 days)	33.08	29.8	39.2	3.69	11.17	29.7
	WFS (28 days)	31.77	22.9	35.7	4.51	14.18	27.6

f_C: Mean compressive strength; SD: Standard deviation; CV: Coefficient of variation; f_{ck}: Characteristic strength compression

Inferential statistical analysis was used to provide a better understanding of the results and to identify whether the mixtures, the fine aggregates, and the curing ages presented statistically significant differences related to the compressive strength (Table 7). When significant differences were found, a multiple comparison test (Tukey's test) was performed at a significance level (α) of 5%.

Table 7: Analysis of variance (ANOVA) for Mix, Sand, Age variables and Mix:Age, Mix:Sand and Sand:Age interactions of the specimens, considering the results of compressive strength.

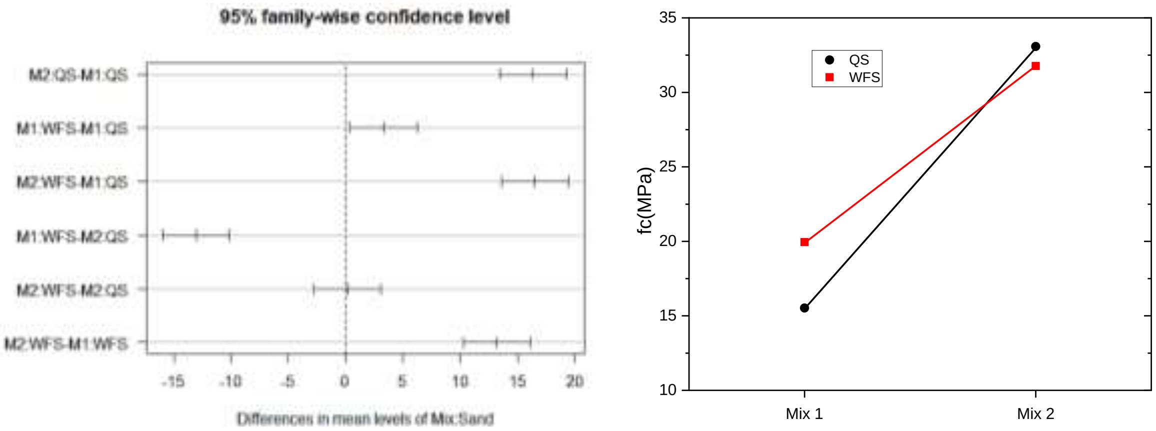
VARIABLES	p-value	
Mix	<2e-16	***
Sand	0.0299	*
Age	0.0299	*
Mix:Sand	0.0462	*
Mix:Age	0.9143	
Sand:Age	0.8129	

Signif. codes: ***: p-value <0.001; **: p-value<0.01; *: p-value<0.05.

According to Table 7, the p-value is lower than the level of significance specified (α = 0.05) for Mix, Sand, Age variables and Mix: Sand interaction. Therefore, the null hypotheses in these cases were rejected, representing a significant difference between the results (Tukey's test was applied|).

Analyzing the results obtained by Tukey´s test, the "Mix" variable showed a mean difference of 14.76 MPa between the mixtures (Mix 2 > Mix 1), and 95% confidence interval for this difference is between 13.21 and 16.32 MPa. Considering the "Sand" variable, the mean difference between fine aggregates (QS; WFS), is 1.73 MPa (WFS > QS), and the 95% confidence interval for this difference is between 0.18 and 3.29 MPa. For the "Age" variable, the mean difference between the two curing ages is 1.73 MPa (28 days > 7 days), and 95% confidence interval for this difference is between 0.18 and 3.29 MPa.

As the variable Mix:Sand presents more than one comparison, its multiple comparison test was presented in the form of a Tukey Graph (Figure 5). The Tukey graph determines whether the differences are significant in practice, the confidence intervals that do not contain zero indicate an average difference that is statistically significant. Considering the Mix: Sand interaction, analyzing the data obtained by the Tukey test, all interactions can be considered statistically different when compared to the compression strength values, except for M2:WFS-M2:QS (Mix 2 with WFS and Mix 2 with QS). Another interaction closer to containing zero is M1:WFS-M1:QS (Mix 1 with WFS and Mix 1 with QS) because they are interactions comparing the same proportion of mix.



(a) (b)

Figure 5: (a) The Tukey's test performed to analyze Mix:Sand interaction with the compressive strength; (b) graph of resistance averages, crossing the variable Mix:Sand.
M1:QS – Mix 1 with quartz sand; M1:WFS – Mix 1 with waste foundry sand; M2:QS – Mix 2 with quartz sand; M2:WFS – Mix 2 with waste foundry sand

When comparing the results of this study to the literature (Table 8), there is no information about the use of WFS in pervious concrete, only other waste solids [42-44]. KARANTH *et al.* [42] improved the resistance of pervious concrete with the adoption of fine aggregate, validating the hypothesis of this study.

Table 8: Results of compressive strength tests with pervious concrete blocks and other values obtained in the literature.

REFERENCE	f_c [MPa]
This study	14.85 – 33.08
NBR 16416 [18]	≥ 20.00
KARANTH *et al.* [42]	13.50 – 28.50
LIMANTARA *et al.* [43]	20.70 – 24.50
LU *et al.* [44]	17.00 – 33.00

3.3 Physical and chemical properties of the solubilized

The results of the solubilized WFS and QS samples were similar (Table 9), so, the use of metallurgical waste in the replacement of quartz sand did not change the physical-chemical characteristics of the pervious concrete solubilized. The alkaline character of the solubilized concrete samples (pH>7) is compatible with the pH of the pervious concrete (>11).

According to MIKAMI *et al.* [45], the presence of alkaline ions in the concrete is responsible for the high pH of the solubilized product. However, the pH tends to decrease over time since in alkaline conditions carbonation of the concrete occurs, consuming $Ca(OH)_2$ of the concrete paste. These chemical reactions are responsible for the alkalinity of the concrete solubilized, as confirmed by the higher levels of total alkalinity of the concrete with higher content of cement Portland (250 kg/m^3).

Table 9: Average results of physical and chemical properties of the solubilized of the WFS and QS samples.

PARAMETERS	UNIT	REFERENCE (WATER)	QS 1	WFS 1	QS 2	WFS 2
pH	-	6.92	11.53	11.75	11.88	11.92
Total Alkalinity	[mg$CaCO_3$/L]	6	422	615	1055	1145
Total Solids	[mg/L]	49	602	722	1166	1256
Total Hardness	[mg$CaCO_3$/L]	0	508	596	1156	1196
Electrical Conductivity	[µS/cm]	9.5	2964	3385	6063	6415

QS 1 – Mix 1 with quartz sand; WFS 1 – Mix 1 with waste foundry sand; QS 2 – Mix 2 with quartz sand; WFS 2 – Mix 2 with waste foundry sand.

The samples solubilized had concentrations of total solids between 602 and 1256 mg/L. There is an increase in the concentration of total solids with the increase of the cement content in the mixture. According to MIKAMI *et al.* [45], the fixed solids probably are the origin of the solubilization of inorganic compounds in cement paste.

The total hardness of the solubilized samples is greater than 300 mg/L of $CaCO_3$, therefore they are defined as so hard because, according to [46], the maximum allowed value (MAV) for the total hardness in drinking water is 500 mg/L.

High electrical conductivity was observed in all solubilized samples, but the WFS sample showing higher values than QS. The electrical conductivity of water indicates its ability to transmit electrical current due to the presence of dissolved substances [46]. The increase in electrical conductivity in Mix 2, which compared to Mix 1 has higher cement consumption, is related to the higher ionic concentration of the solution with higher consumption of cement there are more electrolytes available for the current flow, electron migration in the solution generating greater electrical conductivity.

3.3 Pervious concrete permeability

Table 10 shows the results of the permeability test for pervious concrete mixtures. First, the results indicate that replacing quartz sand with WFS did not alter the hydraulic properties of the two mixtures of pervious concrete paving blocks. When comparing the results of the permeability coefficient (k), mix 2 presented lower values than mix 1 (to QS – 28%; to WFS – 11%). Thus, the main difference between the two mixes is the Portland cement content (≅450 kg/m³), which reduces the void index of the mixture, according to the results of table 5. The fineness module of WFS (1.51) is smaller than that of QS (2.04), which also can justify the decrease in its infiltration capacity, through the reduction of interconnected voids.

According to the permeability test of NBR 16416 [18], the two mixes can be considered permeable because satisfy the minimum requirements (> 10^{-3}), according to the results shown in Table 10. Analyzing the results obtained in the tests, it appears that the mixtures having the lowest voids index (mix 1) have the lowest permeability coefficient value, compared to Mix 2. The research (table 10) concludes that the angular shape of aggregates influences the properties of pervious concrete.

As with the results of the compression test, an inferential statistical analysis of the results of the permeability coefficient was conducted, shown in Table 11, to identify whether the mixes presented significant differences. Analyzing the Mix variable, comparing the mixtures 1 and 2, we obtain a p-value less than the level of significance ($\alpha = 0.05$), presenting a significant difference. Considering the Sand variable, comparing the fine aggregates, QS and WFS, the p-value obtained is higher than the level of significance, no presenting a significant difference.

Table 10: Results of permeability test.

PERMEABILITY COEFFICIENT (k)	MIX 1		MIX 2		INTERVAL k [cm/s]
	QS	WFS	QS	WFS	
ACI 522R-10 [17]					**0.93-1.67**
Average [cm/s]	**1.30**	**1.27**	**0.93**	**1.13**	
Maximum [cm/s]	1.41	1.31	1.02	1.18	
Minimum [cm/s]	1.20	1.25	0.81	1.07	
SD [cm/s]	0.08	0.02	0.08	0.04	
CV [%]	0.06	0.02	0.09	0.09	
NBR 16416:2015 [18]					>0.1
Average [cm/s]	**1.67**	**1.59**	**1.48**	**1.35**	
IBRAHIM [14]					0.15 – 0.28
BATEZINI and BALBO [41]					0.13 – 0.15
LINTZ *et al.* [47]					0.47 – 3.80

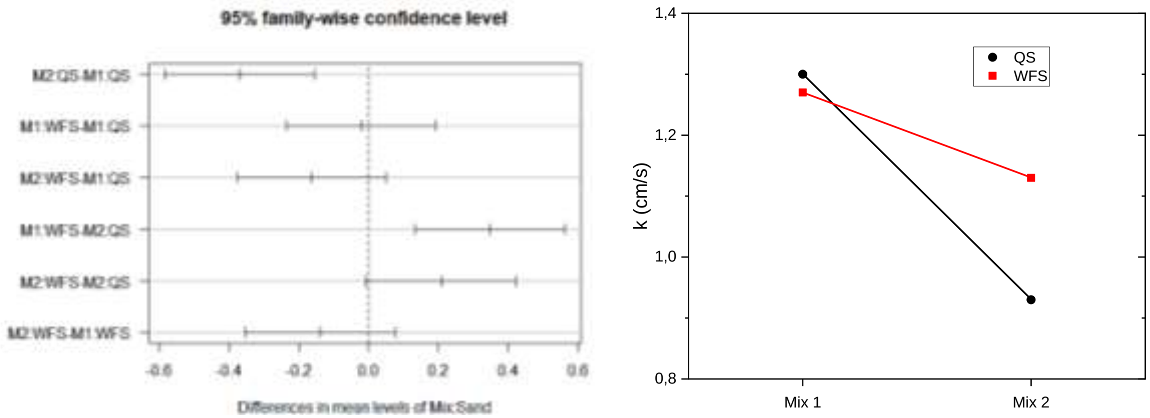
SD: Standard deviation; CV: Coefficient of variation

Table 11: Analysis of variance (ANOVA) for Mix, Sand variables and Mix:Sand interaction of the specimens, considering the results of permeability.

VARIABLES	p-value	
Mix	0.00066	***
Sand	0.08905	
Mix:Sand	0.04137	*

Signif. codes: ***: p-value <0.001; **: p-value<0.01; *: p-value<0.05.

When comparing the interaction between the mixtures and the fine aggregates (Mix:Sand) with the permeability coefficient, the p-value obtained is lower than the level of significance, presenting a significant difference. Thus, the Tukey’s test was performed for this interaction and shows the specimens of mix 1, for both types of sand used, present a significant difference when compared to mix 2 with QS, but not when compared to the mix with WFS (Figure 6).



(a) (b)

Figure 6: The Tukey's test performed to analyze Mix:Sand interaction with the permeability coefficient; b) graph of permeability averages, crossing the variable Mix:Sand

M1:QS – Mix 1 with quartz sand; M1:WFS – Mix 1 with waste foundry sand; M2:QS – Mix 2 with quartz sand; M2:WFS – Mix 2 with waste foundry sand.

3.4 Images of the pervious concrete sample from Scanning electron microscope (SEM)

The images of the pervious concrete (Figure 7), obtained from a Scanning Electron Microscope (SEM) show the microstructure of this material. Figures 7a and 7b represent the general aspect and interface between cement paste/fine aggregate. The pervious concrete consists of small and large conglomerates, chemically associated with hydrated cement compounds. Figures 7a and 7b represent the microstructural images of mix 2 pervious concrete M2-QS and M2-WFS, respectively.

The perfect adherence between the WFS grains and cement matrix (Figure 7b), shows that the adhesion between the WFS and the paste, which was not observed in Figure 7a. According to SANTOS *et al.* [48], the better adherence aggregate/paste can be justified by the presence of bentonite and coal dust in the WFS sample, added during the casting process. Thus, the analyses of images indicate that the use of WFS improved the microstructure of the pervious concretes studied. Nevertheless, the pervious concrete mixes with WFS maintained the desired mechanical and hydraulic properties.

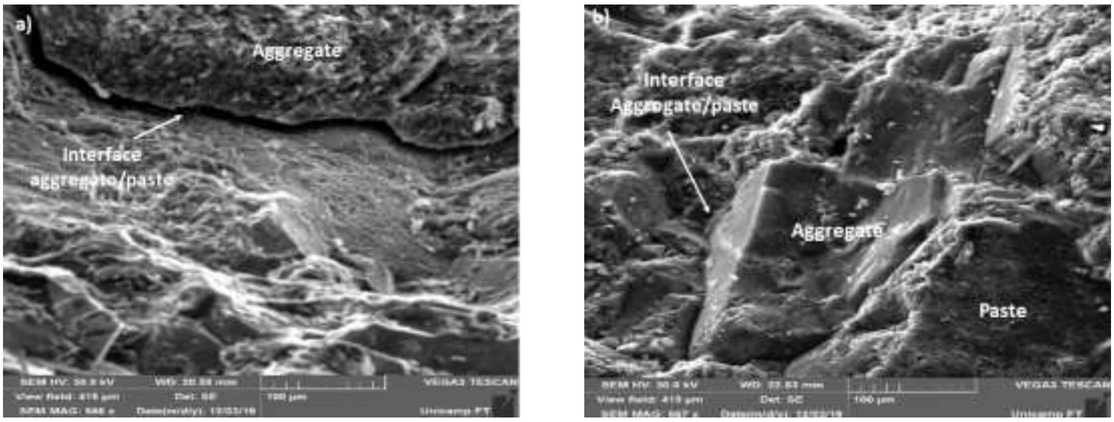


Figure 7: Images obtained from SEM for the pervious concrete samples: a) M2-QS (666x magnification; b) M2-WFS (667x magnification).

4. CONCLUSIONS

When considering the objectives of this study, it is possible to conclude that the use of WFS did not alter the main properties of the pervious concrete (water absorption, compressive strength, and permeability coefficient). The statistical analysis (ANOVA; Tukey's test) showed that the use of WFS improved the compressive strength of pervious concrete blocks without changing their water infiltration and percolation capacity (hydraulic performance). The results obtained from the solubilized WFS, and QS showed close values, so the use of metallurgical residue in place of quartz sand did not change the physical-chemical characteristics of the pervious concrete solubilized. These conclusions indicate that the pervious concrete mixtures analyzed may provide sustainable parameters to the foundry and civil construction sectors, promoting a circular economy and reducing the consumption of natural resources, respectively. It should be noted that the incorporation of WFS in cementitious materials must be studied whenever it occurs changes in the lots of WFS generated, as well as in the molding process used in the foundry.

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