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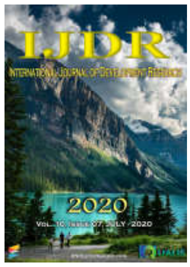

RESEARCH ARTICLE OPEN ACCESS

USE OF FOUNDRY WASTE AS AGGREGATEIN SEMI-DRY PRECAST CONCRETE MIXTURES TO PRODUCE PAVING BLOCKS

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ABSTRACT

The foundry waste generated during the production of cast iron has been studied for being used as a byproduct in civil construction industry. This study evaluated the feasibility of using two types of foundry waste— phenolic sand (PSW) and green sand (GSW)—as partial replacement material of natural fine aggregate to offer technical and environmental advantages.The foundry waste was mixed before using in order to obtain one final product with 60%wt of PSW and 40%wt of GSW. The study evaluated the effect of the foundry waste mix (FWM)as a partial replacement of natural fine aggregate in various percentages (0, 25 and 50%wt)at industrial scale, on the concrete blocks' properties such as mechanical (compressive strength, water absorption, abrasion resistance, porosity index) and structural morphology. Environmental analysis of a concrete block was also assessed. The results with 25% wtreplacement showed satisfying results in compressive strength and abrasion resistance. Nevertheless, the same samples were environmentally classified as Class II A (Not Inert).

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INTRODUCTION

The management of waste since its origin, production, and processing, recycling and final disposalis currently one of the biggest challenges of generating companies, research institutions, government agencies and companies.Foundry industry produces huge amounts of foundry sand waste; its management has become an environmental, economic and social imperative since it is now considered as dangerous waste. The specific applicability of this waste depends on its characterization, whether environmental, chemical, physical or structural, which is a fundamental step to assess the economic feasibility of recycling. Some studies have showed the potential of application of foundry sand waste insever always and in different industry sectors. Zazoghli-Marzouk *et al.* (2014) tested the feasibility of recycling foundry sand stock within subbase layer. The chemical analysis of the byproduct, the formulation of a sub-grade material and its leaching behavior assessed by experimental site were monitored. The results showed that this foundry sand, treated with 5.5% of hydraulic binder, displays acceptable mechanical performances and does not show environmental impacts. The authors concluded with the investigation that this foundry sand could be used in road layers as road materials. In the application of asphalt concrete mixtures, Bakis *et al.* (2006) [14] demonstrated that a fine aggregate replaced with 10% of foundry sand could be suitable. Guney *et al.* (2006) tested foundry sand for highway subbases and found that the strength of a mixture is highly dependent on the curing period, compactive energy, lime or cement presence, and water content at compaction. The resistance of foundry sand-based specimens to winter conditions is generally better than that of a typical subbase reference material. Several studies have been developed with experiments carried out to evaluate the utilization of foundry sand as a substitute material for aggregate in concrete production (Prabhu *et al.,* 2014; Etxeberria *et al*., 2010; Guney *et al*., 2010; Siddique *et al*., 2009). The tests were performed including the characterization of the waste in terms of physical, chemical and mechanical properties; and, in terms of the final product, the density, slump cone, split tensile strength and flexural strength; ultrasonic pulse velocity and compressive strength tests were performed to understand the effects of foundry sand waste on the behavior of concrete. The results obtained show that some formulations produced with the waste satisfy the acceptable limits established by official standards, as well as when compared with reference samples (without foundry sand).

Kraus *et al*. (2009) evaluated the feasibility of the use of foundry sand in self consolidating concrete (SCC). It was concluded that it can be economically viable to produce SCC by using FS as an additive and verified that further research is needed to determine the optimum FS content. Siddique *et al*. (2011) attempted to study the durability and mechanical and micro-structural properties of concrete produced with FS. The results showed that concrete mixtures with FS could lead to good resistance to carbonation and fast chloride penetration. The mechanical properties of the concrete improved with the replacement of FS, and it was recommended that FS be used in concrete production without affecting the mechanical and durability properties. In order to contribute to solve some environmental and technical issues related with foundry sand waste and to turn it into a coproduct, experimental investigation was carried out aiming to use this waste as a fine aggregate replacement in semi-dry precast concrete formulations to produce paving concrete blocks. Based on the results obtained, the optimum proportion of foundry waste mixture (FWM) in paving concrete blocks production was established. Furthermore, the obtained test results were developed at an industrial scale, considering not only the technical issues but also the environmental assessment of the acquired final product.

METHODOLOGY

The characteristics of the foundry waste studied and the method of adding this sand waste into the paving blocks will be presented.

MATERIAL

Binder and conventional aggregates: Brazilian Ordinary Portland cement (OCP) type V ARI RS was used as a binder in the formulations. Its characteristics, including physical properties and chemical composition, are presented on Tables 1 and 2 respectively. Locally sourced materials were used as aggregates; natural siliceous sand (NSS) from a river and basaltic crushed stone (BCG) were used as fine aggregates and gravel (G0) was used as a coarse aggregate.

Foundry Waste: Two types of foundry waste were used in this study: phenolic sand (PSW) and green sand (GSW). Both of the types were generated in the production process of cast iron in a metallurgical industry located in the South of Brazil. The waste was previously regenerated in a mechanical grind process followed by a manual sieving to remove the material retained in a sieve with 1.68 mm mesh diameter. The treatment of PSW and GSW ended with the removal of the remaining metallic material through magnetic separation. Aiming to obtain a satisfactory particle size distribution of the waste and consequently a better packing of concrete, the waste was mixed in adequate percentages (60% of PSW and 40% of GSW) previously. The fineness modulus and the maximum diameter of raw materials are presented on Table 1.

METHOD

Materials and mixes design: The physical and chemical characterization of aggregates and waste was performed. The specific mass and the particle size distribution were determinated according to NBR NM 52 (2009) and NBR NM 248 (ABNT 2003), respectively. Qualitative chemical analysis was developed using X-ray fluorescence spectroscopy (XRF – Shimadzu EDS 720 HS). The loss on ignition was determined using the method described in CEMP 120. The crystalline phases were detected by X-ray diffraction (XRD – diffractometer model 500, Siemens). The morphology of the particles of aggregates and waste was observed through a scanning electron microscope (SEM – EVO LS15, ZEISS). The production of concrete blocks was developed at an industrial scale (Figure 1). The fine aggregates were partially replaced by the foundry waste mix (FWM – 60:40).The proportion of concrete to produce paving concrete blocks is presented on table 1. The aggregates were loaded from the storage silo into the mixer by conveyor belts. Pipes conducted the cement while the water dosage was measured manually. All material was homogenized in the mixer and the ideal point of the concrete was obtained by testingthe "ball point", thus setting up the water/binder ratio for each composition. The mixture was transferred by a conveyor to the mixer device (Rauzi model 715) after its production in the mechanical mixer. Then, it was packed into molds by vibrating to guarantee the appropriate mixture accommodation, and finally it was pressed with the aid of a packing press. The unmolding was performed immediately after this procedure and then the concrete blocks were taken to the curing process. The concrete blocks produced for this study were molded in three classes, considering the cement content and GSW and PSW content (25 and 50%wt of the wastes mixture). The water content of FWM4, FWM5 and FWM6 was increased to guarantee the mixes workability.

Two hundred and seventy-eight concrete blocks were produced with the aim to simulate the conventional production process. From that, samples were selected at 7 and 28 days-curing for characterization. The compressive strength, the water absorption and voids index were performed according to NBR 9781 (ABNT, 2013) and NBR 9778 (ABNT, 2009) rules. The microstructure of the samples was analyzed using scanning electronic microscopy. The abrasion resistance test was also performed in the concrete block’s formulations containing intermediate cement trace (S2, FWM2 and FWM5). The test was performed according to CIENTECA brasion Resistance Test. This method consists in extracting two samples using a diamond circular saw, and then simulating a 500 meters long path traveled by the specimen while being subjected to a constant pressure of 0.06 MPa on abrasive powder. The result of this test is given by the average wear rate of the specimens in millimeters, which corresponds to the average of the differences between the initial and final heights at five points of the specimen. The concrete blocks with the mark and replacement content that showed better results in compression strength test was tested here. The leaching and solubilization tests of milled samples aging 28 curing-days were analyzed according to NBR 10005 (ABNT, 2004) and NBR 10006 (ABNT, 2004).

RESULTS AND DISCUSSION

Raw-material characterization: Natural siliceous sand extracted from a river presented the highest moisture content (5.56%) when compared with the other materials, followed by the GSW (3.24%). GSW presented the highest mass loss, 7.96%wt, followed by FWM (3.86%wt) and PSW (1.82%wt) (Table 4). In terms of mass loss, the foundry sand waste had higher values, as expected, especially the GSW, suggesting thermal decomposition (combustion of organic material) and carbonate decomposition into oxide and CO_2 at high temperatures, as well as hydroxylation of bentonite clay (Carnin *et al*, 2012). PSW result suggests that some of the phenol compounds present in the mold base are transferred into the atmosphere through its volatilization after the casting process, in this case the mold interface region with the liquid metal. Organic additives undergo thermal decomposition within the mold, resulting in volatile compounds formation (Dungan and Reeves, 2007; Carnin *et al*, 2012). The combination between the PSW and the GSW had a significant weight loss of 3.86%wt, which is consistent with the results for the PSW and GSW weight loss individually, considering its composition of 60% and 40% of PSW and GSW. In both the PSW and GSW waste, the main pick observed in the X-ray difractography results was, as expected, the quartz, considering that both are originally siliceous sands. Other crystalline phases were not identified on the samples even with the presence of 4.64%wt Fe_2O_3 and 2.69%wt Al_2O_3 on the chemical analysis (Table 5).

In accordance with the NBR 7211 (ABNT, 2009), the fine aggregates particle size adequate for this type of applicationis between 1.55 and 2.20 mm. As mentioned before, materials with different particle size distribution (out of the standard established zones) can be used as fine aggregate for concrete. Previous studies demonstrate dosage applicability according to the NBR NM 248 (ASME, 2005).The PSW particle size distribution shows that its fineness modulus is lower than the NSS, which was expected due to the standard sand presence, which composes the BCS. Meanwhile, the PSW maximum size is the same as the NSS's. These values are in accordance with the Brazilian Standard. Note that the highest percentage of retained material is located between the sieves with 0.30 mm and 0.15 mm in the grading curve of the PSW, representing more than 94% of the mass.

Figure 2 presents the particle size distribution curve of the raw-material and waste used in this work. It illustrates the FMWcurve, pointing out that the highest percentage of the material mass was retained in the sieves of 0.3 mm and 0.15 mm and most of the remaining material was in the bottom sieve. It is known that an excess of fine particles could damage the concrete compaction of concrete paving blocks and it can be seen that the combination curve of the PSW and the GSW shows high fine particles presence, staying out of the useable area for fine aggregate. The GSW fineness modulus is lower than the NSS and the PSW. This result is below the limit set by the standard established value of useful area for the fineness modulus. Note that the highest percentage of retained material set in the bottom sieves (through the 0.15 mm). The morphology of the PSW, GSW, BCS and NSS performed by scanning electron microscopy is shown on Figure 3. It seems that PSW presents a thin layer of phenolic resin on its surface.

The low presence of resin in some grains may be due to the heating of the metal mold interface. The grains'sub-round shape can favor the packaging either in admixture with the GSW or later in the production of concrete paving blocks. Aggregates with more rounded grains could contribute to the achievement of concrete with greater fluidity, cohesion and a better surface finish. The grains of the PSW are present in several sizes, probably caused by being used in several cycles in the mold manufacturing process. It is important to remember that, after demolding, the waste containing resin is regenerated mechanically and is reused as raw material in new cycles. The GSW grains show their surface partially covered with bentonite and coal, and possibly some residual material from the casting process. According to Powers (1953), in general they have a sub angular morphology. It presents grains with different sizes and its own sand fragments that present an angular morphology. The shape of the grains when in high quantity can harm the concrete consistency, cohesion and the final texture (Fabro *et al*., 2011). The difference in size and the fragments of the grains can be attributed to the crushing and recovery process of the sand (magnetic separation, screening and cooling) and the following re-use during the manufacture of the molding apparatus. This process leads to friction between the grains, thus promoting the breakage and even a change in the morphology of the particles.

Concrete paving blocks: The results of the compressive strength of concrete paving blocks (references and samples with FWM) are presented on Table 6. It was observed that the compressive strength varied around 25% after 7 days of curing in some samples, while the average of the coefficient of variation was around 12.6% and 11% at 7 and 28 days of curing respectively. This change led to an average standard deviation of 2.4 in the first 7 days, except for FWM5, while FWM6 had the highest one of the blocks tested at 7 curing-days, as well as a high coefficient of variation (25%).The average of standard deviation increased to 3.3 after 28 days of curing, mainly due to formulations S2, FWM1 and FWM6 that showed the highest coefficient of variation. The increase in strength was verified after 7 curing-days, especially in reference and replacement traces 1 and 2. This behavior is mainly due to the use of CPV-ARI cement, as previously mentioned. This material provides high initial resistance to concrete. The compressive strength results at 28 days-curing for the three traces (poor, intermediate and rich) can also be observed on Table 6.

It seems that there is a tendency to have a decrease in resistance when associated with the combination of PSW and GSW, maybe related with the packing effect of the waste in the mixture. As expected, concretes with high cement content presented the highest compressive strength with up to 28 days-curing. FWM3 with 25% of PSW/GSW obtained a strength of 37.2 MPa, a value above of the minimum established by the Brazilian traffic legislation. The use of this aggregate replacement in concrete with high cement content for comercial application could be justified if the pavement has been used for high performance. Singh and Siddique (2012) observed that the reduction of the compressive strength with the use of GSW and PSW can be attributed to the increase in surface area of fine particles. It leads to the reduction of the gel in water in the cement matrix, causing the connection process of the coarse and fine aggregates to not occur efficiently.

Nevertheless, Siddique *et al*. (2009) stated that the compressive strength increased with the increase in foundry sand waste for all ages in all the mixes they had tested. They confirmed that the increase in compressive strength with the inclusion of used-foundry sand could probably be due to the fact that used-foundry sand was finer than regular sand, which resulted in adenser concrete matrix, and also due to the silica content present in the tested material. The decrease on strength of concrete blocks using the mixture PSW/GSW may also be due to the weakening of the interfacial area between the paste and the cement byproduct (Carnin *et al*., 2013).

Table 1. Fineness modulus and maximum diameter of raw materials

Parameter	FWM	PSW	GSW	NSS	BCG	G0
Fineness Modulus	1.3	1.7	1.2	1.9	3.0	5.9
Maximum Diameter (mm)	1.2	1.2	2.4	2.4	2.4	6.3

Table 2.Results of physical and chemical characterization of Ordinary Portland cement type V ARI RS (*Lossonignition)

Al_2O_3 (%wt)	SiO_2 (%wt)	Fe_2O_3 (%wt)	CaO (%wt)	MgO (%wt)	SO_3 (%wt)	*LOI (%wt)	Freelime (%wt)	Blaine (cm²/g)	Bulk (g/cm³)
6.39	22.41	3.42	54.74	5.07	1.94	2.81	1.32	4.636	3.0

Figure 1. Concrete blocks production developed at industrial scale

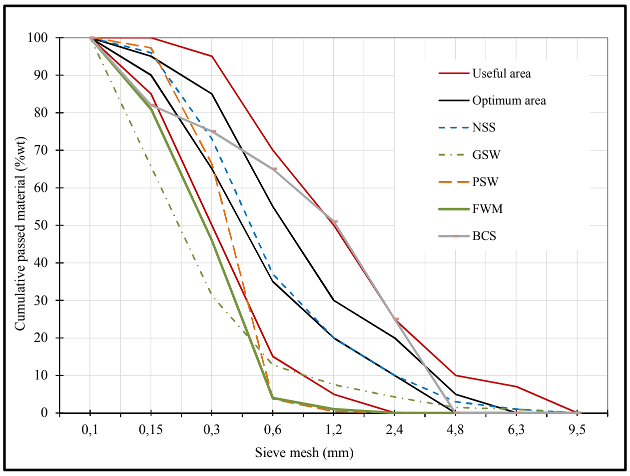

Figure 2. Raw materials, waste and FMW particle size distribution

Table 3. Results of raw-materials characterization

Parameter	FWM	PSW	GSW	NSS	BCG	G0
Moisture content (%wt)	--	1.08	3.24	5.56	2.21	1.28
Specific gravity (g/cm³)	2.2	2.5	2.0	2.5	2.6	--
Losson Ignition (%wt)	3.86	1.82	7.96	0.6	0.4	--

Table 4. Waste chemical composition (%wt)

Samples	ZnO	Fe_2O_3	MnO	TiO_2	CaO	K_2O	Cl	SO_3	P_2O_5	SiO_2	Al_2O_3	MgO
PSW	0.004	0.144	0.001	0.055	0.035	0.265	0.315	0.589	0.224	98.05	0.323	0.001
GSW	0.006	4.644	0.034	0.59	0.635	0.845	0.449	0.751	0.084	89.17	2.693	0.099

Table5. Water absorption and compressive strength of concrete blocks samples (References and samples with partial replacement of NSS by FWM)

Sample	Water Absorption (%)	Voids Index (%)	SD	CV (%)	CS (7 days)	SD	CV (%)	CS (28 days)	SD	CV (%)	Wear Index (mm)
					(MPa)			(MPa)			
S1	7.35	13.47	0.44	7	25.4	2.5	10	35.6	2.3	6	NP
S2	6.33	13.52	0.44	7	19.8	2.2	11	28.4	3.9	14	8.04
S3	5.43	13.44	0.11	2	35.6	2.2	6	42.3	1.9	5	NP
FWM1	7.61	15.45	1.29	17	19.1	2.2	11	31.8	4.1	13	NP
FWM2	7.85	16.03	0.59	7	24.9	3.2	13	25.3	2.1	8	8.32
FWM3	6.53	13.80	0.67	10	16.7	1.9	12	37.2	4.5	12	NP
FWM4	6.90	14.08	2.36	34	14.0	2	15	25.6	3.0	12	NP
FWM5	8.64	17.44	1.14	13	14.1	1.3	10	22.3	2.7	12	14.6
FWM6	7.77	15.70	1.15	15	16.7	4.2	25	32.2	5.1	16	NP

According to Basar and Aksoy (2012), the foundry waste sand can effectively be used in the production of concrete as a partial replacement for fine aggregates without adverse impacts on mechanical, environmental and microstructural properties. However, the authors suggest that the replacement levels should not exceed 20% wt. Carnin *et al*. (2013) also report that satisfactory strength can be achieved using a suitable foundry sand percentage. In general, the lower compressive strength observed in partial replacement with natural sand could be associated to bentonite presence in GSW. This material can be more hygroscopic than natural sand, absorbing water in the concrete preparation, hindering the ideal packaging between the binder and other aggregates. The void ratio tends to increase in samples with less cement, and, hence, have a higher water absorption. The opposite occurs when the NSS substitution content by FWM is increased. According to Carnin *et al.* (2013), high void ratio could mean large pore volume. This can be due to the distribution of voids promoted by the grains' size of the waste, which may lead to a lower compression and therefore a higher pore volume. As shown in Table 6, the result of resistance to abrasion shows that FWM2 (with 25%replacement of NSS by FWM) got a slight variation, about 3%, in the abrasion rate when compared to the reference. That means the replacement content did not affect the abrasion significantly. FWM5 presented high values in relation to the voids ratio (17.44%) and water absorption (8.64%) resulting in the decrease of the mechanical compression strength of blocks recorded in this

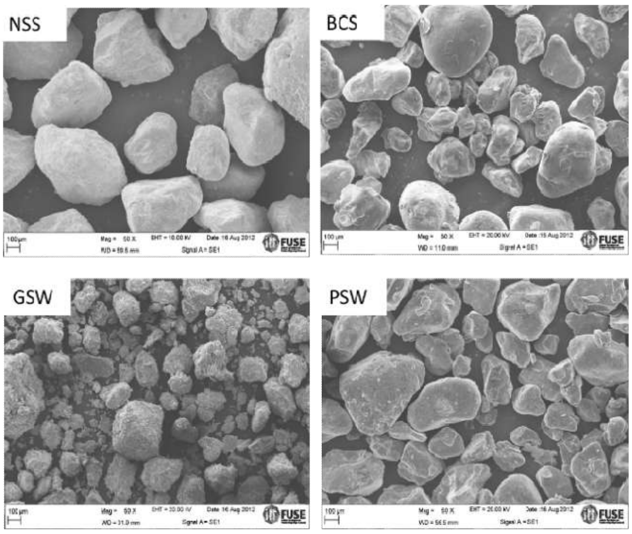

Figure 3. Micrograph of PSW

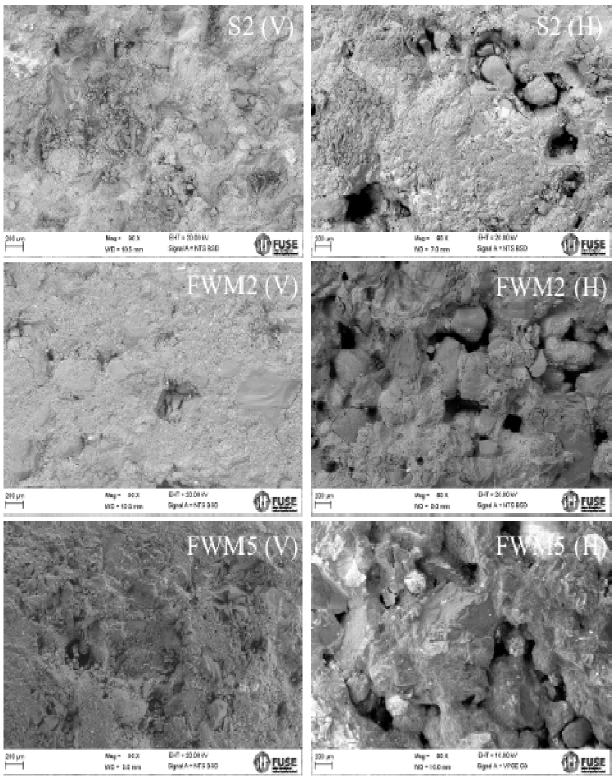

Figure 4. Micrograph of intermediate trace (V – Vertical angle; H – Horizontal angle)

Table 6. Leaching results of concrete blocks with FWM2

Parameter	Unit	Result	*ML (mg/l)
Arsenic	µg/l	< 1.5	1
Barium	mg/l	1.057	70
Cadmium	mg/l	< 0.002	0.5
Lead	mg/l	< 0.008	1
Total chromium	mg/l	< 0.015	5
Mercury	µg/l	< 0.5	0.1
Silver	mg/l	< 0.0015	5
Fluoride	mg/l	1.96	150
Selenium	µg/l	< 2.0	1

*ML = Maximum Limit established according to NBR 10005

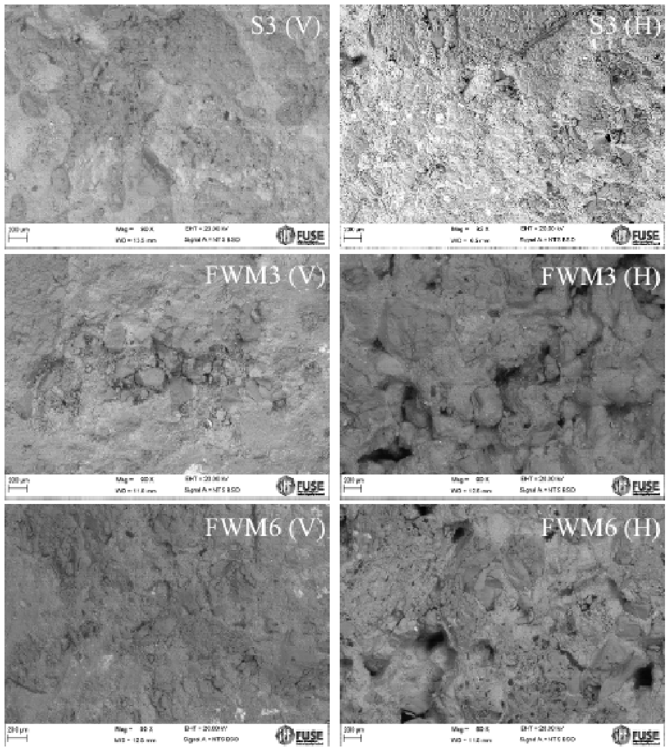

Figure 5. Micrograph of rich trace (V – vertical angle; H – Horizontal angle)

Table 7. Solubilization results of concrete blocks with FWM2

Parameter	Unit	Result	*ML (mg/l)	Parameter	Unit	Result	*ML (mg/l)
Aluminum	mg/l	0.284	0.2	Mercury	µg/l	< 0.5	0.001
Arsenic	µg/l	< 1.5	0.01	Phenol	mg/l	< 0.001	0.01
Barium	mg/l	0.02	0.7	Nitrate	mg/l	0.179	10
Cadmium	mg/l	< 0.002	0.005	Cyanide	mg/l	< 0.0003	0.07
Sodium	mg/l	47.06	200	Sulfate	mg/l	1.26	250
Copper	mg/l	0.048	2	Surphactants	mg/l	0.321	0.5
Zinc	mg/l	< 0.100	5	Chloride	mg/l	26.3	250
Lead	mg/l	< 0.008	0.01	Fluoride	mg/l	0.496	1.5
Total chromium	mg/l	< 0.015	0.05	Silver	mg/l	< 0.0015	0.05
Iron	mg/l	0.429	0.3	Selenium	µg/l	< 2.0	0.01
Manganese	mg/l	0.205	0.1				

*ML = Maximum Limit established according to NBR 10006

formulation. The sample also showed a high abrasion index, which, in this case, had a variation of approximately 82% when compared with the reference trace, indicating significant interference of FWM in this parameter. The high pores content may have contributed to the worst FWM5 mechanical performance when compared to the other formulations tested. The structural analysis of the samples was performed by scanning electron microscopy (SEM) in the formulations 2 and 3 (intermediate and rich cement traces) and the results are presented on Figures 4 and 5, respectively. S2 (H) and FWM2 (H) present several pores in their structure, indicating low level of packing of the aggregate and binder mixture, which could lead to the low compressive strength values obtained by these formulations. The formulations with the incorporation of FMW may have led the grains with the presence of bentonite to absorb a higher percentage of water when compared to the other formulations, hindering the consolidation of the concrete mass and causing the high volume of pores. Putting in contrast the samples analyzed in Figure 4, the reference sample S3 (high cement content) showed a slightlyporous structure, consistent with the results of the water absorption and consequent high compression resistance (Figure 5).FWM2 and FWM5 showed a similar structure when compared tothe FWM3 sample, mainly in the horizontal position with the presence of some pores, but in a smaller amount. The concrete blocks results for the solubilization and leaching are shown on Tables 7 and 8 respectively. It can be observed that only the Al and Fe levels are presented above reach the maximum limit established by the Brazilian Standard defined for solubilization parameters considering solid waste. The XRF results confirm the high content of these elements when compared to the other elements. According to NBR 10.004, the mixture of waste (FWM) is classified as a Class II – Non-Inert.

Conclusion

According to the results of this study, the following conclusions can be drawn:

- Regarding the partial substitution of natural fine aggregate sand by the FMW, the concrete blocks had lower compressive strength results when compared to the reference blocks after 28 days-curing;
- The highest average value of compressive strength at 28 days-curing was observed for the cement rich trace, with 25% of natural sand replacement by FMW, reaching 37.2 MPa strength, higher than the minimum required by the NBR 9781 (ABNT, 2013) in paving blocks used in the commercial vehicle traffic line;
- Apart from FWM5, which is the intermediate trace with 50% of natural sand replacement by FMW, all other traces obtained compressive strength up to 25 MPa after 28 days-curing, which, according to Scott Hood (2006), can be considered a feasible value for concrete blocks to be used in floors that have smaller vehicle or pedestrian traffic requests, but do not meet the minimum standard required by 35 MPa;
- The abrasion index decreased with the increase of the natural sand content replacement for FWM. Technically, there is no difference between the mean values of the abrasion rate in blocks with 25% substitution of natural sand when compared to the mark. That is, this content does not influence significantly the results obtained;
- The increase in the natural sand content level by FMW lead to the water absorption of the blocks increasing; even with the increased water absorption of the blocks with replacement in relation to the reference blocks, the values are below the maximum limit of 10% required by NBR 12118 (ABNT, 2011);
- According to the result of the leaching and dissolution analysis, the sample containing the concrete block casting waste residue was classified as class IIA - Inert not according to NBR 10004 (ABNT, 2004);
- It is possible to ensure that foundry sand waste is successfully used in cement blocks applications replacing fine aggregates, such as natural sand, mainly if the particle size distribution is carefully arranged.

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