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Use of electric arc furnace slag for producing concrete paving blocks

Uso de escória de forno elétrico na produção de peças de concreto para pavimentação

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Abstract

In this study the electric arc furnace slag was used as coarse natural aggregate substitute in concrete paving blocks production. The concrete mixture was defined by using weight proportions in the ratio of 1:2:3:0.51 (cement:sand:coarse aggregate:water) in order to obtain a compressive strength of 35 MPa. Four groups of concrete were prepared: a reference recipe and three others with the slag replacing the natural aggregate in the proportions of 25%, 50% and 75%. The compressive strength was not influenced by the slag content; however, it was influenced by the curing age, as the sample with 75% of slag addition had its compressive strength increased by 13.5% from 7 to 56 days. Water absorption presented a slightly reduction with slag addition. The results of compressive strength and water absorption met the Brazilian technical requirements, making the paving blocks suitable for use in light vehicle traffic. The results obtained in this study highlight the influence of the production process in the final quality of the steel slag, and the need of stablishing technical and environmental requirements to guide and promote the safe use of electric arc furnace slag in concrete.

Keywords: Construction materials. Alternative materials. Electric arc furnace slag. Paving blocks. Concrete.

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Resumo

A escória de forno elétrico foi usada como substituto do agregado graúdo natural na produção de peças de pavimentação de concreto. O traço de concreto 1:2:3:0,51 (cimento:areia:agregado graúdo:água) foi definido para alcançar uma resistência à compressão de 35 MPa. Quatro grupos de concreto foram preparados: um traço referência e três outros com a escória substituindo o agregado comum nas proporções de 25%, 50% e 75% (em massa). A resistência à compressão não foi influenciada pelo teor de escória, no entanto, foi influenciada pelo tempo de cura, uma vez que a amostra com 75% de escória apresentou 13,5% de aumento na resistência aos 56 dias em relação aos 7 dias de cura. A absorção de água apresentou uma pequena redução com a adição da escória. Os resultados da resistência à compressão e absorção de água atenderam aos requisitos das normas técnicas brasileira, indicando que os blocos podem ser utilizados para pavimentação de tráfego leve. De maneira geral, os resultados deste estudo destacam a influência do processo produtivo na qualidade final da escória, e a necessidade do estabelecimento de legislação e normas técnicas específicas, para nortear e promover o uso seguro da escória de forno elétrico em concreto.

Palavras-chave: *Materiais de construção. Materiais alternativos, Escória de forno elétrico. Peças de pavimentação. Concreto.*

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Introduction

Steel is a metal alloy composed of iron, carbon and other compounds; its production currently is performed by the Oxygen Converter (Linz and Donawits - LD or Blast Oxygen Furnace - BOF) and Electric Arc Furnace (EAF) processes (FRONEK, 2012; LOBATO *et al*., 2015). The EAF process is responsible for over 40% of steel produced worldwide. It is a more competitive and sustainable process, as it uses metal scrap as basic raw material (PELLEGRINO *et al*., 2013), and during this process, the EAF slag (EAFS) is produced.

EAFS generation rate corresponds to 15-20% of the steel production (CHUNLIN *et al*., 2011). Considering that in 2015 the Brazilian steel production reached 33 million tons (BRAZILIAN…, 2016), it is estimated that an average of 5 million tons of EAFS was produced in the country. According to the current Brazilian environmental regulation, EAFS is considered an industrial waste (generally classified as non-hazardous and inert waste), and therefore, the commercialization and recycling is allowed case by case, based on the analysis of chemical and leaching data of a specific slag, according to its intended use. The standard NBR 16364 (ABNT, 2015) provides technical requirements for the use of steel slags in road bases and sub-bases. However, up to now there is no technical and environmental guidance on the use of EAFS in concrete materials, making it difficult to widespread the use of this by-product in construction applications in general.

After being removed from the furnace and cooled, the EAFS becomes a stony, hard and black material, with a chemical composition constituted mainly by calcium, iron and silicon oxides (over 80% in weigh) and aluminum, magnesium, manganese and phosphorus oxides (ARRIBAS *et al*., 2015). Physical and chemical characteristics of EAFS make its use as an alternative aggregate very attractive. However, the presence of free calcium and magnesium oxides (which are well known as expansive compounds) may cause volumetric expansiveness in concrete (ROJAS; ROJAS, 2004; PELLEGRINO; GADDO, 2009). This issue has been extensively studied, and according to Arribas *et al.* (2015), the use of EAFS as a concrete aggregate is accepted if its maximum volumetric expansion is 1%. Wang *et al.* (2010) state that the proportions of the expansive oxides, as well as the concentration of other components in EAFS vary with the raw materials, type of steel, furnace conditions, and other steel processes specifications, and considering these variations, each slag must be carefully analyzed before determining a specific use.

The construction sector is among the largest consumers of resources, and therefore, it is essential to look for alternative materials in order to reach the sustainability of the production chain. In this regard, many researches have evaluated the use of EAFS as a substitute of natural aggregates in concretes, such as the studies of Arribas *et al.* (2014), Papayianni and Anastasiou (2010), Manso *et al.* (2006), among others.

Considering that Brazil is among the largest producers of steel in the world, and consequently, produces considerable quantities of steel slags, and also, that there is a need to encourage the use of this by-product as a material, this article aims to evaluate the use of an EAFS as a substitute of natural aggregate in paving blocks manufacturing.

The motivation for studying the EAFS substitution in concrete paving blocks, is due to the fact that in Brazil there is a high demand for improving the conditions of sidewalks, streets and vicinal rods. According to ABCP (ASSOCIAÇÃO…, 2017), concrete paving blocks present many advantages, such as: easy installation and maintenance, which allow the use of local materials and labor; the light color that increases the reflective capacity of the pavement (saving energy for street lighting), and also reduces the absorption of heat (improving thermal comfort and decreasing the formation of heat islands in urban centers). The non-slip surface offers greater safety and reduces braking distance; if properly installed, the paving blocks allow the flow of rainwater into the groundwater, preventing floods; the paving blocks adjust to the environment, avoiding shrinkage and cracking, and may be manufactured in different colors, shapes and dimensions, at a relative low cost compared to natural stone blocks.

According to the literature, studies related to the use of steel slags in South America, and specifically in the Brazilian context are scarce, as most of the available studies have been developed in European countries. Moreover, to the authors' knowledge, there are no studies, both in national and international literature, reporting results of the use of EAFS in paving blocks, considering the conditions of slags produced in Brazil. This panorama highlights the need of better understanding the behavior of EAFS in concrete products, in the specific Brazilian context. Then, this study may provide scientific basis for a broad discussion, evolving the national technical and environmental committees, seeking for the proposal of guidelines and standards for the safe use of EAFS as a natural aggregate substitute in concrete.

Electric arc furnace slag production and characterization

The EAFS used in this study is produced in a semi-integrated facility that produces long carbon steel, located in Southeast Brazil, where the steel scrap is the main raw material (Figure 1). The scrap is fed into the electric arc furnace and then, the graphite electrodes are lowered into place, starting the scrap fusion. The liquid EAFS, after chemical adjustments, is removed from the furnace and poured into cast carbon steel containers and transferred to an external area, where it is cooled through water spraying. At this time, due to the thermal shock caused by the contact with the cold water, the slag is fragmented into asymmetric blocks, named gross EAFS.

After completely cooled, the EAFS is transported to a processing unit, where the remaining metallic fraction is removed, and then the slag is crushed, screened, and transformed in a by-product named electric arc furnace aggregate (EAFA), with different particle size grades (0 - 4.75mm; 4.75 - 9.51mm; 9.51mm - 19mm; 19mm - 50.8mm).

Until 2008, the gross EAFS was stored mixed with the ladle furnace slag (produced in the ladle furnace, where the temperature and composition adjustment of the molten steel occur); this practice affected negatively the EAFS, as the ladle furnace slag has a high content of free CaO and MgO. Aiming to improve the quality of the EAFS and its recyclability, after July 2008, the company adopted the practice of segregating both slags in the generation source.

Currently, an average of 10,000 ton/month of EAFS is produced, recycled and sold for use in roads base and sub-base; also, the total amount of LFS produced is landfilled.

According to the NBR 10004 (ABNT, 2004), the EAFS produced in this facility is classified as non-hazardous (based on leaching test results - Table 1) and inert waste (based on the solubilization test results - Table 2).

As already mentioned, the presence of free calcium and magnesium oxides may cause hydration and expansion phenomena when the EAFS is used as aggregate in concrete production, and for this reason, some authors report the use of a stabilizing treatment, which consists of exposing the EAFS to outdoor weather with regular water spraying for about 90 days (PELLEGRINO *et al.*, 2013). The EAFS used in this study was tested for expansibility potential, right after the slag cooling, according to the NBR 16364 (ABNT, 2015), resulting in a value of 0.05%. The test consists of preparing three specimens of compacted EAFS in a mold, in which a device is connected in order to provide a pressure of 10 lb; the mold and the device are attached to an extensometer, submerged in pre-heated water (38 ºC). The water-submerged sample is transferred to an oven at 71±3 ºC; after 30 minutes in the oven the height is measured (Hi). The test is conducted for 14 days, and after that, the final height is measured (Hf). The expansibility is then calculated according to Equation 1:

$$\% \text{ Expansibility} = [(Hf - Hi)/116.4] \times 100 \qquad \text{Eq. 1}$$

It is important to mention that in this study, the recycled EAFS is named electric arc furnace aggregate (EAFA). A sample of EAFA with particle sizes between 4.75-9.51 mm was collected directly from the company's stockyard and used for all the tests carried out in this study. The chemical composition obtained by X-ray fluorescence (XRF) shows that iron (38.2%), calcium (24.5%) and silicon (18.4%) oxides are the main compounds (Table 3). These values are similar to the ones found by Manosi *et al.* (2016).

Figure 1 - **Schematics of the steelmaking process, depicting the generation of EAFS and its management**

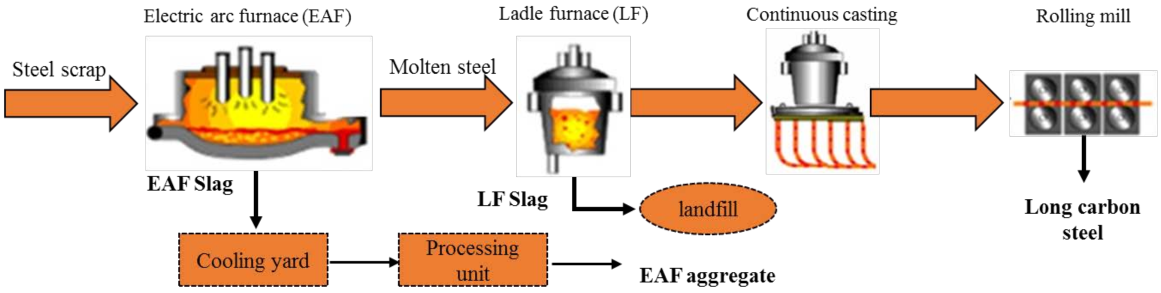


Table 1 **- Leaching test results obtained for EAFS, according to NBR 10004 (ABNT, 2004)**

Parameter	Concentration (mg/l)	Threshold limit
Arsenic	<0.01	1.0
Barium	2.00	70.0
Cadmium	<0.001	0.5
Lead	0.0232	1.0
Chromium (total)	<0.01	5.0
Fluorides	0.1	150
Mercury	<0.00008	0.1
Argentum	<0.01	5.0
Selenium	<0.008	1.0

Table 2 **- Solubilization test results obtained for EAFS, according to NBR 10004 (ABNT, 2004)**

Parameter	Concentration (mg/l)	Threshold limit
Aluminum	<0.01	0.2
Arsenic	<0.01	0.01
Barium	0.123	0.7
Cadmium	<0.001	0.005
Lead	<0.001	0.01
Cyanide	<0.05	0.07
Chloride	2.87	250
Copper	<0.005	2.0
Chromium (total)	<0.01	0.05
Iron	0.103	0.3
Fluoride	1.06	1.5
Phenols	<0.01	0.01
Manganese	0.0427	0.1
Mercury	<0.00008	0.001
Nitrate	<0.1	10.0
Argentum	<0.01	0.05
Selenium	<0.008	0.01
Sodium	9.49	200
Sulfate	14.6	250
Surfactants	<0.1	0.5
Zinc	0.0743	5.0

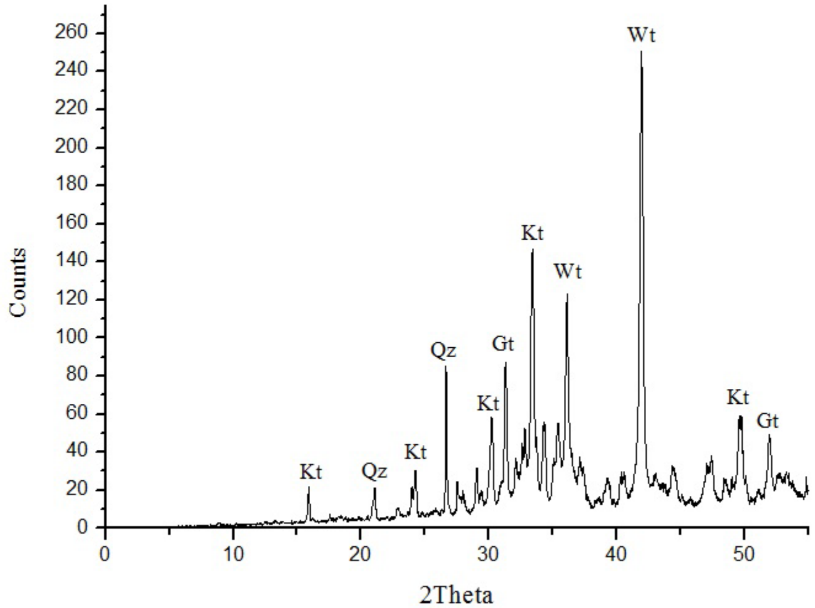
Table 3 **- Chemical composition of EAF aggregate obtained by XRF**

Components	Concentration (%)	Components	Concentration (%)
Na_2O	0.130	Cr_2O_3	1.170
MgO	5.99	MnO	3.790
Al_2O_3	5.25	Fe_2O_3	38.20
SiO_2	18.40	CuO	0.022
P_2O_5	0.807	ZnO	0.013
SO_3	0.467	SrO	0.077
Cl	0.020	ZrO_2	0.034
K_2O	0.037	Nb_2O_5	0.028
CaO	24.50	MoO_3	0.007
TiO_2	0.800	BaO	0.144
V_2O_5	0.117	WO_3	0.020

X-ray diffraction (XRD) measurements were performed to analyze the mineral compounds present in the EAFA sample, by scanning the sample with a Bruker D8 Endeavor diffractometer with a Cu tube. It was operated at 40 kV and 40 mA, with 2ϴ steps of 0.02 and 0.1 s of acquisition time. The identification of crystalline phases was obtained by comparing sample diffractogram with PDF2 database of ICDD – International Centre for Diffraction Data. The XRD diffraction patterns (Figure 2) show that the main mineral compounds identified were wustite ($Fe_{0.925}O$; PDF 89-0686), kirschsteinite ($CaFe^{2+}SiO_4$; PDF 34-0098), gehlenite ($Ca_2Al(AlSi)O_7$; PDF 89-5917) and quartz (SiO_2; PDF 87-2096). These compounds are present in the main rocks used for natural aggregate production in Brazil (basalt, diabase and granite). Instable compounds, such as free lime and periclase were not identified.

Figure 3 shows the comparison of the appearance of the natural (a) and EAF (b) aggregate used, and Figure 4 the microstructure analysis obtained by scanning electron microscope (SEM), showing a heterogeneous and slightly porous surface of EAFA.

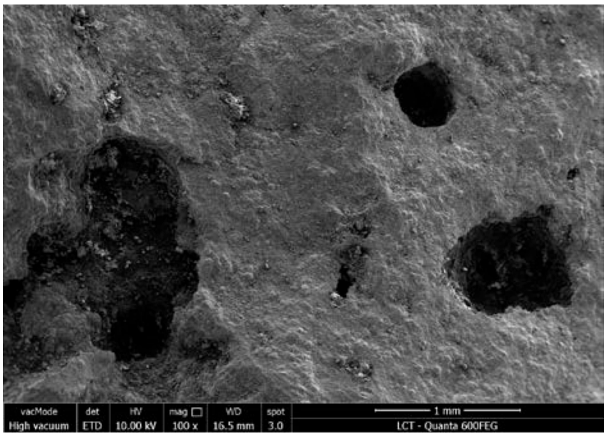
Figure 2 **- XRD pattern of EAF aggregate used in concrete paving blocks**



Note: peaks are labeled:
Wt – wustite;
Kt – kirschsteinite;
Gt – gehlenite; and
Qz – quartz.

Figure 3 **- (a) Natural aggregate and (b) EAF aggregate appearance**

Figure 4 **- SEM image of EAF aggregate with 100x of the magnification, showing the presence of some pores**



Methodology

This section presents the characterization of the materials used for the paving blocks manufacturing (cement, fine and coarse aggregates), as well as the test methods used to characterize the blocks. The concrete and the paving blocks were produced in a laboratory scale, following standardized Brazilian methods.

Materials characterization

A Brazilian CPV ARI Portland cement was used for all concrete mixes. Figure 5 shows the particle size distribution of fine (sand and stone dust) and coarse aggregates (natural aggregate and EAF aggregate), obtained by sieving, according to NBR NM 248 (ABNT, 2003).

Table 4 shows the physical properties of aggregates. Density and water absorption of coarse aggregates were determined according to NBR NM 53 (ABNT, 2009a) and densities of fine aggregates were measured according to NBR NM 52 (ABNT, 2009b). The water absorption content of EAFA is lower compared to natural aggregate, as already found by other authors (PELLEGRINO *et al*., 2013; FALESCHINI *et al*., 2015). It is important to mention that the water absorption content of EAFA is intrinsically related to porosity, and it depends on the production process (specially the cooling phase). Summaya *et al*. (2016) have compared the EAFS properties obtained by different authors, and found values ranging from 0.7 to 3.37%.

It is important to mention that the results for particle size distribution have also met the requirements of the Standard NBR 7211 (ABNT, 2009). This standard establishes threshold values for production of aggregates from natural origin for use in concrete; for coarse aggregates it requires tests for particle size distribution, shape index, resistance to abrasion (Los Angeles test), harmful substances and durability, besides other tests that may be required for special uses. The result for shape index, obtained according to NBR 7809 (ABNT, 2008), classifies the EAFA as a cubic aggregate. The resistance to abrasion obtained by the Los Angeles test, performed according to NBR NM 51 (ABNT, 2001) resulted in a value of 18.4%, which is within the limit for coarse aggregates (< 50% in mass basis); a similar result was found by Manosi *et al*. (2016). The analysis of the other parameters required by the Standard NBR 7211 were not performed because the scope of this standard does not include aggregates produced as product or by-product of industrial processes, and also, because they were not within the objective of this study.

Paving blocks production and test methods

Preliminary lab tests were performed to establish the proportion of components in the concrete mixture, in order to obtain a compressive strength of 35 MPa for light vehicles. The water content needed to arrive at the designed consistency was tested, and then the mixture proportioning was defined by using weight proportions in the ratio of 1:2:3:0.51 for the components cement:sand:coarse aggregate:water. Considering the defined mix proportion, four groups of concrete were prepared, including a control concrete without slag addition, and the others with EAF aggregate replacing the gravel in the proportions of 25%, 50% and 75%.

Figure 5 **- Particle size distribution of the aggregates (sand, stone dust, natural aggregate and EAF aggregate) used for concrete mixes**

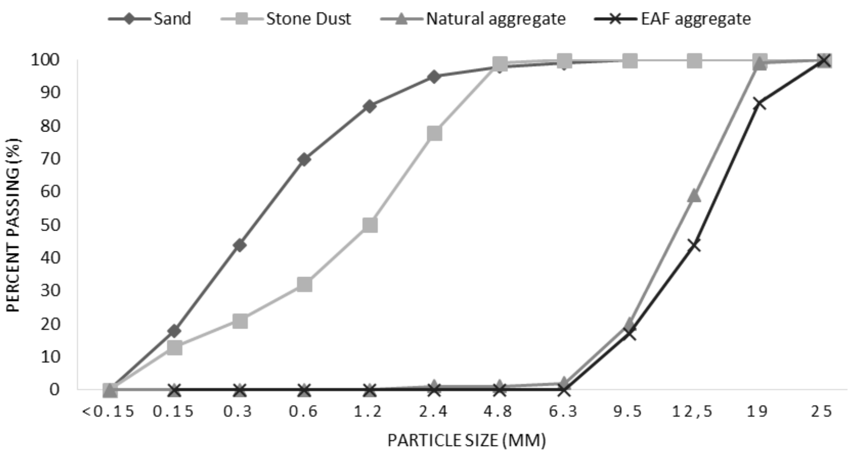


Table 4 **- Physical properties of the aggregates used for concrete mixes**

	Fineness modulus	Maximum characteristic size (mm)	Specific mass (g/cm³)	Water absorption (%)
Sand	1.89	1.2	2.66	0.3
Natural aggregate	6.79	19	2.85	1.6
EAF aggregate	6.96	25	3.65	0.9

Concrete workability was determined by the slump cone test, according to NBR NM 67 (ABNT, 1998). Paving blocks were produced by using rectangular plastic molds (200 x 100 x 60) mm^3. For each group of concrete, 24 blocks were molded (7 for compressive strength test at each curing age – 7, 28 and 56 days, and 3 for the water absorption test at curing age of 28 days). The mixtures were prepared with a mechanical mixer for a period of 8 min. The molds were filled in two stages; in the first stage, a layer of concrete was poured into the mold and compacted on a shaking table for 30s; more concrete was then added until the mold was full and compacted on the shaking table for 30 seconds more. The molds were initially placed into a moist chamber for 24 h, and after that, the blocks were demolded, measured and then returned to the chamber for cure by immersion for 7, 28 and 56 days. After curing, blocks were left to dry for the compressive strength tests according to NBR 9781 (ABNT, 2013) by using a Universal Testing Machine with a maximum capacity of 120 ton, and a compression load rate of 0.5 ± 0.2 MPa/s. Figure 6 shows the paving blocks with the different percentages of EAFA incorporation, showing that the aggregate does not interfere in the color. Water absorption at 28 days was determined according to ABNT NBR 9781 (ABNT, 2013).

Scanning Electric Microscopy (SEM) coupled with Energy Dispersive X-Ray Spectroscopy (EDS) of a piece of concrete with 75% of EAFS incorporation was performed in order to observe the interaction between the EAFS aggregate and the paste matrix microstructure.

Results and discussion

Results of the slump test for the concretes prepared for paving blocks production show an increase in the slump with the increased EAFA percentage (Table 5). As the natural aggregate has higher water absorption capacity (1.6%) compared to EAFA (0.9%), when higher percentages of natural aggregate are substituted by the EAFA (50% e 75%), maintaining the same water/cement ratio, an increase in the slump is verified.

Figure 6 **- Paving blocks with 75%, 50%, 25% and 0% of EAF aggregate incorporation after curing for 56 days**

Table 5 **- Slump test results obtained for fresh concrete prepared for paving blocks production with EAF aggregate in different percentages**

EAF aggregate (%)	Slump (mm)
0	35
25	35
50	50
75	70

Compressive strength slightly increased from 7 to 56 days, and with the EAFS incorporation, compared to the control (Table 6). These results were statistically analyzed by using Stat graphics Centurion XVI Software, and it was found that the percentage of EAF aggregate incorporated do not interfere in compressive strength with a confidence level of 95% and p-value < 0.005. But the curing age affected the results, with a statistically significant difference between the three ages. The standard deviation (SD) was calculated, considering 7 repetitions for each age, showing a higher variation in the results at 28 days (with a SD between 4.1 e 6.9 MPa). It is important to note that the compressive strength increased at 56 days, for the blocks with 15% and 75% of EAFA. This might be due to the water present in the EAFA surface, which provided the hydration of the anhydrous cement still present in the mixture.

According to Coppola *et al.* (2016), the rough and porous surface of EAFS may improve the adhesion of aggregate to the cement paste (physical adherence), thereby increasing the mechanical strength of the concrete.

Moreover, the chemical adhesion develops with the curing age, thus contributing to the strengthening of the transition zone of the aggregate and cement paste, which explains the mechanical strength increase with time observed in this study. This effect was more pronounced in the blocks with EAFA incorporation, than in the blocks prepared with natural aggregate. The transition zone, with a perfect adherence of a particle of EAFA evolved by the cement paste may be seen in the SEM image of a broken piece of paving block with 75% of EAFA (Figure 7a), and the EDS analysis reveals the main chemical compounds present in the XRF analysis (Figure 7b).

In the SEM images of Figures 8, 9 and 10 it is possible to identify the compounds of cement hydration (portlandite and CSH, ettringite and hydrated monosulphate (C_4ASH_{18}), respectively. According to Metha and Monteiro (2014) these compounds are responsible for the resistance and hardness of cementitious matrix of concrete; with the concrete ageing, part of the ettringite of the paste becomes hydrated monosulphate.

Results for water absorption tests at 28 days (Table 7) presented a small reduction as the EAFA percentage increases. Compressive strength and water absorption are inversely related; a highwater absorption percentage indicates a high porosity in the hardened concrete material, reducing, consequently the mechanical strength. A similar behavior has been found in a study of Penteado *et al.* (2016), in which a polishing ceramic waste was used in concrete paving blocks; according to Gencel *et al.* (2015), this behavior is explained by the fact that the aggregate particles are enveloped by the cement paste, and then, the pores of the EAFA do not contribute to the water absorption in the concrete block.

The results obtained for paving blocks also met the technical requirements, as NBR 9781 (ABNT, 2013) requires a minimum compressive strength of 35 MPa and a maximum 6% of water absorption in paving blocks for light vehicle traffic.

Table 6 **- Compressive strength test results obtained for paving blocks, at 7, 28 and 56 days**

EAF (%)	Average Compressive strength (MPa)					
	7days	SD_7	28 days	SD_{28}	56 days	SD_{56}
0	39.3	4.8	47.8	5.1	47.1	4.3
25	42.2	1.7	42.8	6.9	45.3	2.7
50	42.9	2.3	42.8	5.7	49	2.9
75	42.9	3.6	46.3	4.1	48.7	3.1

Figure 7 **- (a) Transition zone of concrete with 75% of EAFA obtained by SEM; (b) EDS coupled highlighting the chemical compounds of the aggregate**

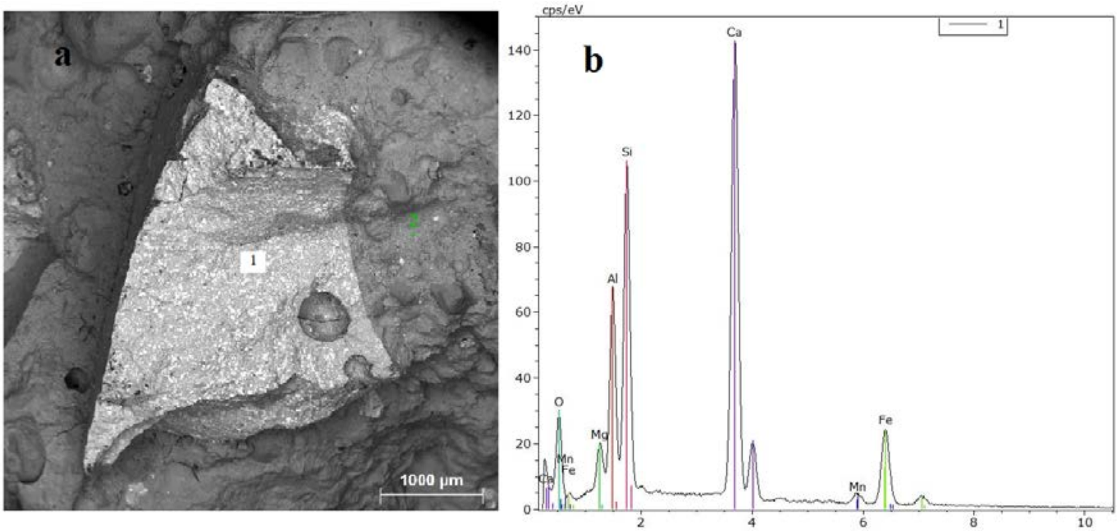


Figure 8 **- SEM image of concrete with 75% of EAFA, with the presence of portlandite and C-S-H compounds**

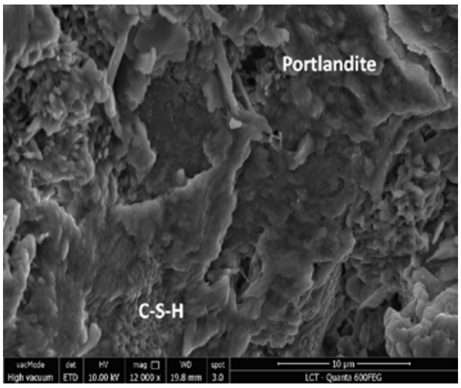


Figure 9 **- SEM image of concrete with 75% of EAFA, with the presence of ettringite**

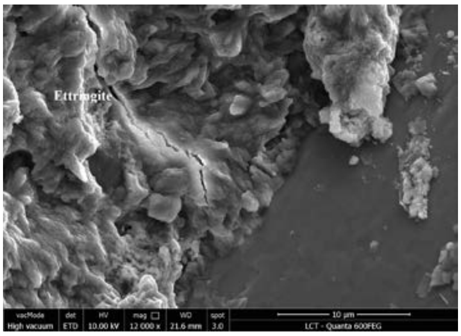


Figure 10 **- SEM image of concrete with 75% of EAFA, with the presence of hydrated monosulphate (C_4ASH_{18})**

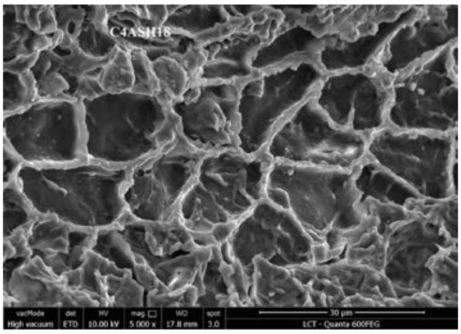


Table 7 **- Water absorption results at 28 days**

EAFA (%)	Water absorption (%)
0	3.5
25	2.9
50	3.1
75	2.9

Conclusions

This study evaluated the use of electric arc furnace aggregate (EAFA) as substitute of natural aggregate in the manufacturing of paving blocks. The results show that the aggregate produced from EAFS may replace the natural aggregate to produce paving blocks. The key findings are:

(a) the workability of concrete measured by slump test increased with the electric arc furnace aggregate addition, as the water absorption content in the EAFA used in the study was higher than in the natural aggregate;

(b) the EAFA content does not appear to affect the compressive strength, however, this parameter was influenced by the curing age, as the sample with 75% of EAFA addition had its compressive strength increased by 13.5% from 7 to 56 days;

(c) SEM micrographs of the concrete sample with 75% of EAFA addition showed a perfect adherence of an aggregate particle evolved by the cement paste, and identified compounds of cement hydration (portlandite and CSH, ettringite and hydrated monosulphate);

(d) water absorption presented a slightly reduction with EAFA addition, compared to the reference concrete.

(e) the results of compressive strength and water absorption met the Brazilian technical requirements (ABNT, 2013) for using paving for light vehicle traffic.

However, it is important to emphasize the importance of EAFS management, as some steel facilities store this slag mixed with ladle furnace slag, making the use of EAFS in concrete unfeasible, due to the high content of expansive compounds. Finally, a comprehensive environmental and economic analysis of EAFS use is recommended, to evaluate all possible impacts and benefits. Therefore, based on these results, a broad discussion and the establishment of technical and legal requirements considering the local context, is necessary in order to ensure the safe use of EAFS as an aggregate.

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