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RESEARCH ARTICLE

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CONCRETE BLOCK WITH INCORPORATION OF BSSF STEEL SLAG: ALTERNATIVE FOR ENVIRONMENTALLY APPROPRIATE DISPOSAL OF A WASTE FROM THE STEEL INDUSTRY

Leandro H. Benittez*, Fernanda G. S. Ferreira and José da C. Marques Neto

Postgraduate Program in Civil Engineering, Federal University of São Carlos, São Carlos, Brazil

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Corresponding author:
SANTOS, Heloisa dos

ABSTRACT

The incorporation of waste generated by the steel industry in cementitious components can contribute regionally, in a sustainable way, to a significant reduction in environmental liabilities. This study aimed to analyze the physical and mechanical characteristics of concrete blocks without structural function manufactured with BSSF steel slag as a replacement for natural aggregates. Partial substitutions of 20, 40, 60, 80% of the natural aggregates were made by artificial ones in the production of the blocks. In addition to the BSSF steel slag, Portland cement, natural sand, gravel, stone powder, additive and water were used in the manufacture of blocks. The concrete blocks were manufactured in a cement industry and the entire manufacturing process was detailed. Then, the blocks were tested for dimensional analysis, water absorption, liquid area and resistance to compression at 28 and 371 days of age. With the durability study, the viability of incorporating BSSF steel slag into concrete blocks was proven, since the blocks produced met the normative requirements and still had an increase in quality.

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INTRODUCTION

The introduction of sustainability concepts and practices in civil construction has evolved over time and part of this advance includes the use of waste that was once discarded and is now recycled and reused. The road to an ideal scenario is still long, but many studies in the area of waste use for the production of new assets have been growing and demonstrating the benefits achieved by such action. Civil construction is a large consumer of natural aggregates and perhaps because of this it needs to contribute to the reuse and recycling of waste from the sector itself and from others in its processes, being described by some authors as an industry with great recycling potential. Thus, the sector contributes to the reduction in the use of natural aggregates, collaborating to reduce the exploitation of these finite resources. About 50% of the natural resources consumed worldwide are the responsibility of the construction industry, which makes it, in a way, responsible for the use of recycled aggregates as a substitute for natural aggregates (Faria, 2007; John, 2000; Angle, 2011).

Melt shop slag is one of the residues that originate from steel production. 100 to 150 kg of steel slag is generated per ton of liquid steel processed (CSP, 2021). In the year 2019 Brazilian steel production was 32.6 million tons and the world production was 1.87 billion tons, so around 4.89 and 280 million tons of steel slag were generated in Brazil and the world, respectively. Brazil ranked ninth in world steel production that year, accounting for 1.7% of total production. This ranking was led by China being responsible for 53.1% of all steel produced in the year worldwide (IABR, 2020). The best known steelmaking waste used for over 100 years by cement makers as an addition to cement is the blast furnace slag, extracted in the steel reduction process. The steel mill slag comes from the steel refining process and does not yet have a well defined destination. In Figure **1**, the simplified schematic flow of the steel production process is shown. In civil construction, the use of steel slag is very limited, mainly due to the expansive characteristics of the material. The slag can only be used after being stabilized, i.e., undergoing a process that makes it less chemically reactive. About 44% of the stabilized slag produced is used in infrastructure works such as highways, stabilization of bases and sub-bases, railroad ballast, and others.

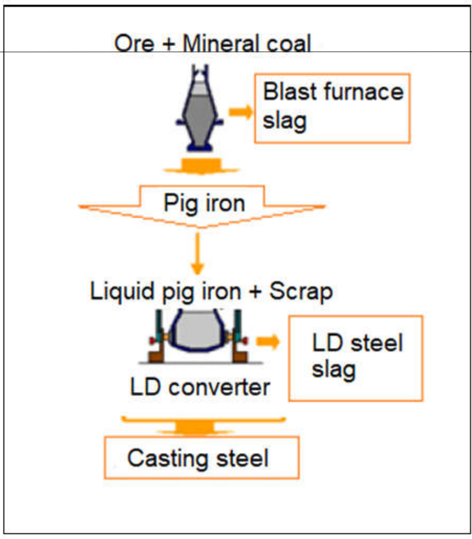


Figure 1 - Simplified schematic flow of the steel production. Source: Masuero (2000)

The remainder, about 56%, is stored in steel mill yards, causing major environmental liabilities (Raposo, 2005; Silva, 2011; Baltazar, 2001). The chemical and mineralogical composition of steel mill slag is composed of CaO, SiO2, MgO, FeO, Fe2O3 and calcium silicates, dicalcium ferrite, wustite of variable composition, free CaO and free MgO among other species, which vary according to the steelmaking processes, type of refining, raw materials, additions, scrap and cooling speed (Chotoli, 2006). According to NBR 10004 (ABNT, 2004) steel mill slag is classified as non-inert solid waste, class IIA, i.e., it is not hazardous to use. However, this type of waste can cause environmental impacts if improperly disposed of in soil and water, because it presents properties of biodegradability, combustibility or water solubility. The stabilization process of steel slag is carried out in two ways. The most common way and the one most used by steel mills around the world is as follows: the steel mill slag is transported still in a liquid state, with temperatures of 1,400 to 1,700°C, generally in pans on rails, to the cooling bays, where the material is tipped and later cooled. The cooling can be air cooling, pelletizing or abrupt cooling with water. The way the slag is cooled directly influences the physical characteristics that the material will have. After cooling, the slag goes through the crushing process where magnetic recovery and sieving take place for material classification. Through electromagnet conveyors, the metallic fractions are recovered and will be reused as scrap in the new steel production process. The remaining slag is separated, classified and stored in open air yards for a stabilization process, with a minimum period of six months. After this period, they are sold as a co-product of steel production (Geyer, 2001; Faria, 2007). **Error! Reference source not found.** illustrates the main phases of the steel slag processing process.

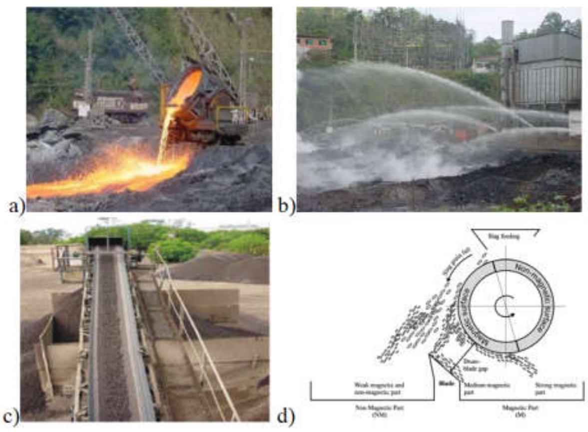


Figure 2. Processing of steel slag. a) Liquid slag; b) Cooling; c) Classification. Source: Adapted from Souza (2007). d) Magnetic separation. Source: Alanyali et al. (2006).

The other form of processing of steel slag was developed by the Chinese company Baosteel Metal Company and is known as BSSF (Baosteel's Slag Short Flow). This method is innovative and used in only three steel mills in the world, one of which is located in the state of Ceará, in Brazil, CSP - Companhia Sideúrgica do Pecém. The great differential of this method is that it cools and stabilizes the steel slag instantly. The process consists in throwing the slag, still in a liquid state and at high temperatures, into a rotating container, with the presence of metallic balls and the addition of water. The great advantage is that through this process the slag is solidified and ground into small particles. In addition, the residual metal does not mix with the slag at the time of unloading, due to the different solidification points. The entire process takes three to five minutes to produce cooled, ground and stabilized steel mill slag. It still significantly reduces the amount of unreacted free lime, the main element responsible for the expansive property of the material (Energy, 2015; Souza, 2016).
Figure shows the processing of steel slag by the BSSF method.

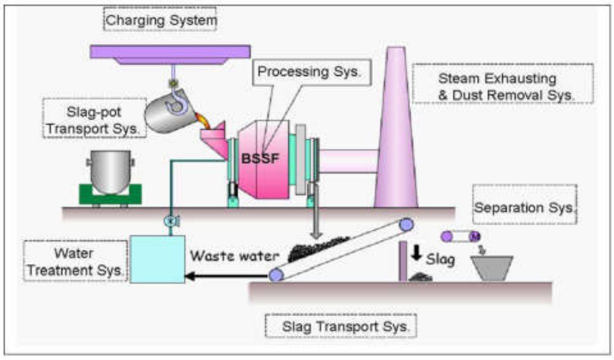


Figure 3. Beneficiation of steel slag by the BSSF process Source: Guangqiang & Hongwei (2011)

The main problem that hinders the use of steel slag in construction is its expansive properties, due to the presence of free lime oxide (CaO) and free magnesium oxide (MgO). The steel mill slag can present destructive expansion either in hydration, car-bonation or oxidation. Therefore, the use of this material in civil construction requires great care. With the adoption of criteria with limit values and classification parameters, it is possible that this material can be used, because after the curing time, it reaches stabilization through the formation of stable products (Machado, 2000). The use of steel slag in civil construction, as a substitute for natural aggregates, besides bringing environmental gain, brings savings, since recycled aggregates have much lower prices compared to natural aggregates (Santos, 2012). Yanik (2019) points out that in a short period of time, the dust produced from recycled concrete aggregate, fly ash or slag, will surpass the current consumption of natural sand and pebbles. The trend is that this will occur in large urban centers, since natural deposits will be far from the point of use and, therefore, the production of recycled aggregate will be more viable than transporting the natural aggregate. One of the most commonly used materials in building works, with about 90% of its composition made of natural aggregates, are concrete blocks. By definition, concrete blocks are masonry components, with or without structural function and standardized by NBR 6136 (ABNT, 2016) and NBR 12118 (ABNT, 2013). They are cast on the upper and lower faces and have a net area equal to or less than 75% of the gross area. They are produced by manual, pneumatic or hydraulic equipment through vibro-compaction and immediate extrusion (Fernandes, 2015). As for the physical and mechanical requirements that ensure the quality of concrete blocks, the NBR 6136 (ABNT, 2016) determines the limits of strength, water absorption, dimensional and linear shrinkage by drying. Several works are carried out in Brazil and worldwide with the use of steel slag as a substitute for natural aggregates for concrete production. However, with the BSSF steel slag, because it is a very published on the production of concrete and mortar and no published work on the production of concrete blocks. Motivated by the environmental concern regarding the large waste generation by industries, especially the steel industry, and the wide use of concrete blocks in civil construction, this paper studied the potential of partial replacement of natural aggregate by artificial (recycled), from steel slag BSSF, in the manufacture of concrete blocks without structural function (sealing). For greater confidence of the results, the durability of the blocks was studied, with dimensional analysis tests, water absorption, net area and compressive strength at 28 and 371 days. The physical and mechanical properties of the blocks were analyzed through laboratory tests provided in NBR 6136 (ABNT, 2016) in order to validate the study regarding the use of this material in the market.

MATERIALS AND METHODS

The materials used in the research were natural aggregates, normally used for the manufacture of concrete blocks, such as natural quartz sand, pebble and stone powder of basaltic origin. The binder was Portland Cement CPV ARI, due to the large amount of clinker (from 95 to 100%) and few additions (from O to 5% of limestone filler), which makes it ideal for manufacturing precast concrete, due to its high initial resistance. As recycled aggregate, BSSF steel mill slag was used. Besides the materials cited, a plasticizer additive and water were used to produce the concrete block. The characterization of the aggregates and binder, the manufacturing process of the blocks and the results of the tests on blocks are presented below.

were analyzed for grain size, according to NBR NM 248 (ABNT, 2003) and the acceptable limits and optimal use limits proposed by NBR 7211 (ABNT, 2009). The natural sand and the stone powder showed a fineness modulus of 2.2, being within the optimal zone of use for concrete. The size distribution curve of the pebble was below the limit of the range 4.75/12.5, however, it is used in concrete blocks due to the small wall thickness (around 24 mm), which allows using pebbles with a maximum size of 9.5 mm. The BSSF steel slag used in this study presents a well distributed granulometric curve with maximum dimension (Dmax) equal to 12.5 mm and fineness modulus of 4.35. Besides the particle size analysis, the aggregates were tested for unit mass, void volume, specific gravity and powder content. The results are presented in Error! Reference source not found.. For steel slag, in addition to the tests performed previously, loss on ignition tests were performed according to NBR NM 18:2012 (ABNT, 2012) and semi-quantitative chemical analysis by X-ray fluorescence (XRF), based on general guidelines of NBR 14656 (ABNT, 2001). For this, we used an X-ray fluorescence spectrometer brand Panalytical model Minipal Ce-ment, from pellets fused in a fusion machine brand Claisse model M4, using melts based on mixture of lithium tetraborate / lithium metaborate brand MAXXIFLUX (66.67 % of Li2B4O7, 32.83 % of LiBO2 and 0.7 % of LiBr), with a ratio of 0.6 g of sample and 6.75 g of melt. Free calcium oxide (free CaO) according to NBR NM 13 (ABNT, 2012), as well as Iron II oxide (FeO) and metallic iron (FeM) according to ASTM E246 guidelines (ASTM, 2010). Quantitative mineralogical analysis by X-ray diffraction was performed in a Panalytical model EMPYREAN X-ray diffractometer with a PIXcel3D detector,

Table 1 - Physical characterization of the aggregates. Source: Authors (2020)

EVALUATED PROPERTIES		ABNT STANDARD	MEDIUM SAND	STONE POWDER	STONE CRUSHED	STEEL SLAG BSSF
Unit mass (kg/m³)	Loose state	NBR NM 45:2006	1480,18	1809,41	1618,14	2079,31
	Compacted state		1576,61	1960,57	1687,24	2128,02
Volume of voids (%)	Loose state		42,34	29,65	47,43	39,01
	Compacted state		38,58	23,77	45,19	37,58
Apparent specific mass in dry state (g/cm³)		NBR NM 52:2002; NBR NM 53:2009	2,56	2,57	3,07	3,41
Specific mass in SSS condition (g/cm³)			2,58	2,70	2,85	3,50
Absolute specific mass (g/cm³)			2,60	2,97	2,75	3,74
Powder content (%)		NBR 46:2003	0,11	21,25	-	1,74

Note 1: The loss on fire value is negative, possibly due to oxide-reduction phenomena that occur in the loss on fire test, inherent to the material tested.

Table 2. Chemical and mineralogical analysis of BSSF steel slag. Source: Authors (2020).

CHEMICAL ANALYSIS			
DETERMINATIONS	**RESULTS, IN %**	**DETERMINATIONS**	**RESULTS, IN %**
Loss on Fire (PF)	-0,5 [Note 1]	Aluminum oxide (Al_2O_3)	1,4
		Phosphorus oxide (P_2O_5)	1,4
Calcium oxide (CaO)	37,3	Titanium oxide (TiO_2)	0,6
Total iron (Fe)	27,2	Iron metal (FeM)	0,6
Iron oxide II (FeO)	21	Vanadium oxide (V_2O_5)	0,2
Ferric oxide (Fe_2O_3) [Note 2]	14,6	Potassium oxide (K_2O)	0,1
Silicic anhydride (SiO_2)	13,2	Chromium oxide (Cr_2O_5)	0,1
Magnesium oxide (MgO)	6,6	Sulfuric anhydride (SO_3)	0,1
Manganese oxide (MnO)	3,5	Strontium oxide (SrO)	< 0,1
Free calcium oxide (CaO)	1,8	Copper oxide (CuO)	< 0,1
MINERALOGICAL ANALYSIS			
COMPOUNDS OR MINERALOGICAL PHASES	**MOLECULAR FORMULA**	**STRUCTURE SHEETS**	**RESULTS, IN %**
Wuestite	FeO	96-900-2670	21,8
Borwnmillerite	$Ca_8Fe_{6,37}Al_{1,63}O_{20}$	96-900-3342	20,3
---	$Ca_{14,92}(PO_4)_{2,35}(SiO_4)_{5,65}$	96-810-3588	16,7
Larnite	CaO_2SiO_3	96-901-2795	16,5
		96-901-2791	
Periclase	MgO	96-900-6460	10,1
$Ca_2Fe_2O_5$	$Ca_2Fe_2O_5$	96-210-6287	6,6
Kirschsteinite	$Ca_4Fe_{3,08}Mg_{0,88}Si_4O_{16}$	96-900-5316	3,7
Cohenite	Fe_3C	96-901-4399	3,3
Hematite	Fe_2O_3	96-900-0140	1

Note 2: The determination of iron oxide (Fe2O3) was obtained by stoichiometry with the following equation: Fe2O3 = ((Total iron (Fe) - (Iron Oxide II (FeO) x 0.78) - metallic iron (FeM))) x 1.43.

diffractometer and structure standards provided by the free COD (Crystallography Open Database) database (updated in 2017) and, eventually, diffractometer and structure standards from ICDD (International Center for Diffraction Data) and ICSD (International

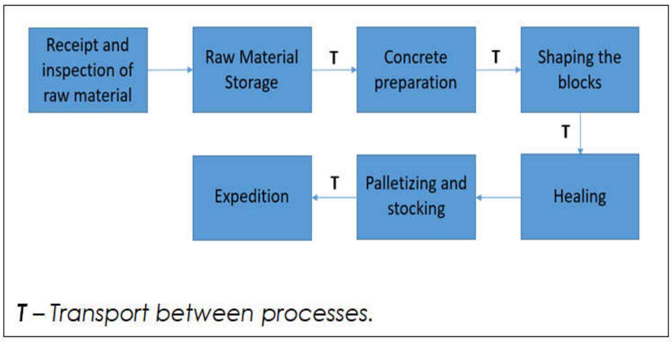
The production process begins with the reception and inspection of the raw material. Concretize works with aggregates that are already characterized in the laboratory. The great advantage of always using the same aggregates is the invariability of the raw material, which guarantees the same characteristics of the raw materials. The binder used is CPV ARI, which provides high initial resistance. The need for

(Goodness of Fitting), in addition to the graph of the differences between the observed and calculated diffractograms. Some of the refinement parameters used in each diffractogram to obtain the percentages of the phases present are presented below, in the respective order of application: scale factor refinement; baseline adjustment; refinement of the diffractometer constant (Zero Shift); refinement of the unit cell of major phases; refinement of the unit cell of minor phases; refinement of the peak profile (for phases present with more than 5%); refinement of the preferential orientation (for susceptible compounds). Error! Reference source not found. shows the chemical and mineralogical composition of the BSSF steel slag used. As for the binder, chemical analysis, physical and mechanical tests were performed as specified in NBR 16697 (ABNT, 2018) and the results presented in Error! Reference source not found..

Table 3. Characterization of the cement. Source: Authors (2020)

Characteristics and Properties		**Values Obtained**	**Limits of nbr 16697 (abnt, 2018)**
Paste of normal consistency (% cement mass)		28,5	*
Start of setting		02h20min	> 60 min
End of setting		03h15min	< 600 min
Hot expansion (mm)		0,5	≤ 5
Cold expansibility (mm)		1,0	*
Specific mass (g/cm³)		3,09	*
Fineness	Retained 75µm (#200)	1,1	< 6,0%
	Specific area	5480	*
Compressive strength (fcj)	1 day	25,5	> 14 MPa
	3 days	35,7	> 24 MPa
	7 days	40,5	> 34 MPa
	28 days	48,1	*

Manufacture of the blocks: In this stage of the research, a work of production management of the concrete blocks was carried out, detailing each manufacturing process, as well as the composition used in the factory for the production of the blocks, including the compositions chosen for the present work. The manufacturing of the blocks in the research in a factory and not in a laboratory was due to the intention of production in scale and possible commercial application of the block studied. Through the flowchart in Figure 4, it becomes clearer the understanding of each stage of manufacturing of the blocks.



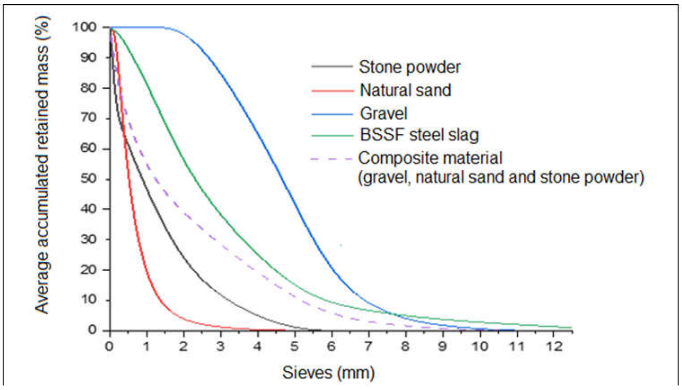
Source: Authors (2020)

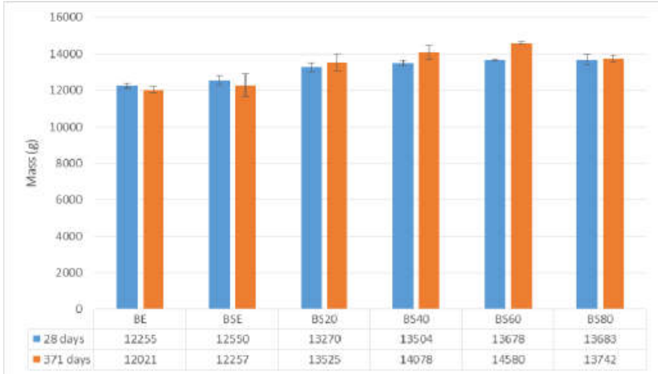
Figure 4. Flowchart of the production of the blocks

palletized the very next day and transported to the company's stockyard.

The storage of the raw material is done in bays with concrete floors and physical separation of the aggregates, in order to avoid contamination with the soil or even mixing them. There is a disvantage of the bays not being covered, which makes the aggregates subject to the weather. The binder and additive are stored inside the shed, to avoid contact with humidity and close to the mixer where they will be used. The concrete is prepared in a mixer that is responsible for the homogenization of the aggregates, binder, additive and water, which are inserted, in the correct amounts, according to the composition defined for each product, as well as to the block's final desired resistance. After preparation, the concrete is poured by gravity onto the inclined conveyor belt, which transports it to the vibro-press machine. The concrete blocks are molded in the hydraulic vibro-press machine, which has as principle the pressing of the concrete, with a high weight load, about 6 tons, at the same time that it uses the vibration of the mold, two vibrators driven by two engines of 5 hp each, to provide better densification of the material. The type of block to be manufactured is changed according to the mold attached to the machine, which in turn has the function of molding the concrete that will be vibrated and pressed. Concretize uses a Permaq MBHD 4 hydraulic vibro-press machine.

The blocks are made on rectangular naval plywood boards, which are removed from the machine by a horizontal conveyor belt. Upon entering the belt, the blocks go through the last manufacturing process, which is the removal of the edges by a cylindrical brush. Next, the blocks are stored in the shed, side by side, for curing. The curing process begins with the covering of the blocks with plastic sheeting. The use of the tarpaulin has the function of conserving the humidity and temperature, i.e., it prevents the blocks from losing humidity to the environment and also provides a closed system with a higher temperature, since the cement reaction is exothermic and releases heat. The curing process takes approximately 12 hours and is carried out at night when the company is not working. In the morning the tarpaulin is removed, the blocks manufactured the day before are palletized and sent to the outside area to be stocked by the company. The quantity of blocks per pallet depends on the model. For the 14x19x39 fence block, object of the research, 114 blocks are placed per pallet. The blocks remain in stock for a minimum of 5 days, with the purpose of gaining mechanical resistance and later being commercialized. In the second stage of the research was carried out the definition of the compositions (mixtures) to be studied. For this, it was performed the packing of the particles in the laboratory, through the unit mass test, according to NBR NM 45 (ABNT, 2006), aiming to find a composition with the lowest voids index (composition pebble/sand and then pebble + sand / stone powder). This composition with the lowest void index was the reference for the proposed substitutions. Blocks were also manufactured with the composition used by the company in order to compare the results. In a particle size comparison, it was observed that steel mill slag presents a behavior close to the packaged composition found in the laboratory, i.e., similar percentages of coarse and fine aggregates, as shown in Figure 5. Therefore, it was decided to substitute coarse and fine aggregate by slag.





Source: Authors (2020)

Figure 6. Dry mass of the blocks Source: Authors (2021).

For all compositions, the amounts of water and additive were fixed, so that the only variable in the different compositions was the substitution of natural aggregates by artificial ones. The substitution of natural coarse and fine aggregates by artificial ones from BSSF steel slag was done in the proportions of 20, 40, 60, and 80%. A 100% substitution was attempted, however, due to the lack of cohesion (lack of fines in the mixture), the blocks broke when coming out of the mold. The nomenclature used for each block was as follows:

- Company Block – BE;
- Packaged Suggestion Block - BSE;
- Block Substitution 20% - BS20;
- Block Substitution 40% - BS40;
- Block Substitution 60% - BS60;
- Block Substitution 80% - BS80.

The unit compositions, in volume, of the concrete blocks studied are presented in **Error! Reference source not found.**. The water/cement ratio used for all mixes was 1.25 and the amount of additive was set at 50 ml. To convert cement from mass to volume, a unit mass of 1.08 kg/dm³ supplied by the cement manufacturer (Apodi) was used. The blocks manufactured were of the type without structural function, class C, with dimensions of 14x19x39 cm. They were produced following the same processes used by the Concretize factory.

Table 4. Unit compositions in volume Source: Authors (2020)

INSUMES	BE	BSE	BS20	BS40	BS60	BS80
Cement	1,00	1,00	1,00	1,00	1,00	1,00
Gravel	4,32	3,29	2,65	1,94	1,30	0,65
Natural sand	4,32	2,38	1,89	1,46	0,97	0,49
Stone powder	4,32	7,29	5,83	4,37	2,92	1,46
BSSF steel slag	-	-	2,59	5,18	7,78	10,37
Cement consumption (kg/m³)	118,21	116,62	117,52	118,44	119,37	120,32

Testing the blocks: For greater credibility of the results obtained in the work, tests were performed at advanced ages of the blocks produced, i.e., durability, including tests prescribed in NBR 12118 (ABNT, 2013), with requirements presented by NBR 6136 (ABNT, 2016). They included tests at ages of 28 and 371 days. The tests performed were: dimensional analysis; water absorption and net area; and axial compressive strength. ANOVA statistical analysis was performed to observe variance between results and Tukey's test to identify which results had significant difference.

RESULTS

For the purpose of knowledge and possible comparison of the blocks with different levels of substitution, Figure 6 shows the mass of each block at the different ages at which the tests were performed.

This is important information, because the mass of the blocks interferes directly in the density of the masonry and with this the possibility of altering the structural designs of the buildings. Besides the projects, the difference in block mass can interfere in the process of material delivery, since road transport is normally used to transport the materials. This evaluation of the mass gain is not the object of this research, but the information is useful for advances in future work. Comparing results of the blocks masses in relation to the BSE block (reference), in the tests with age of 28 days, we have: BE 2.35% less dense; BS20 5.74% more dense; BS40 7.60% more dense; BS60 8.99% more dense; and BS80 9.03% more dense. For the trials at 371 days, one has: BE 1.92% less dense; BS20 10.34% more dense; BS40 14.86% more dense; BS60 18.95% more dense; and BS80 12.12% more dense.

The results of the tests prescribed in the standard are presented below.

Dimensional analysis: The results of the dimenonsional analysis tests for width, height, and length of the blocks at ages 28 and 371 days are shown in Figure 7.

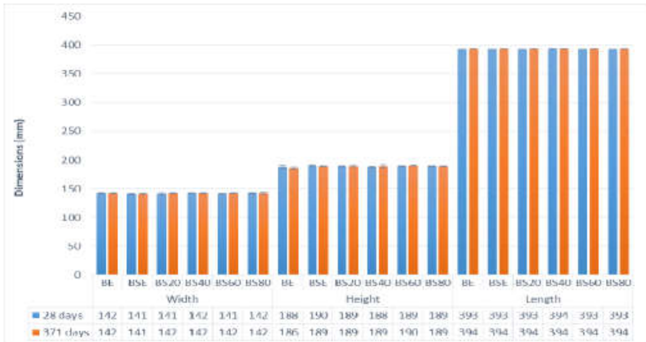


Figure 7. Results of the dimensional analysis tests
Source: Authors (2021).

According to NBR 6136 (ABNT, 2016), the allowed dimensional tolerances are ± 2 mm for width and ± 3 mm for height and length, with tests at 28 days. The variations in width of the blocks tested were a maximum of 1 mm between each other and up to 2 mm in relation to the nominal dimension, meeting the normative requirements. For height, the maximum variations were up to 2 mm, compared to each other for the same replacement, that is, comparing BE with BE, BSE with BSE, and so on. The BE block with an age of 371 days presented a variation of 4 mm in relation to the nominal dimension, being above the normative limit. The other blocks presented height variation of up to 2 mm, in relation to the nominal dimension, meeting the normative requirements. For the length, there was a maximum variation of 1 mm among all blocks. However, in relation to the nominal dimension, the BS40 block with 28 days and the other blocks with age of 371 days, presented dimension of 394 mm, exceeding in 1 mm the normative tolerance. In relation to the thickness of the walls, longitudinal and transversal, the normative tolerance is - 1.0 mm. The blocks tested presented, on average, wall thicknesses of 24 mm, and for blocks without structural function, class C, it must be at least 18 mm. As for the equivalent thickness, the referred norm presents as a minimum value 135 mm/m and the blocks tested presented an average of 188 mm/m, also exceeding the minimum recommended in 39%.

Water absorption and net area: According to NBR 6136 (ABNT, 2016), for concrete blocks without structural function, class C, water absorption should be individually less than 11% and on average less than 10%. Figure 8 shows the results. All blocks produced in the research met the normative requirements for water absorption. In general, the absorption increased from 28 to 371 days of age. The biggest variation identified in the results was for the BS40 block, with an increase in water absorption of around 25%, but it is worth noting that its standard deviation was high, 2.3. Comparing the water absorption of the reference block with the others, at an age of 28 days,

lower; BS20 18.87% lower; BS40 7.55% higher; BS60 11.32% higher; and BS80 47.17% lower.

DISCUSSION

The main objective of this work was to evaluate the physical and mechanical performance of concrete blocks without structural function, manufactured with partial replacement of natural aggregates by artificial aggregates from BSSF steel slag, including durability results with tests at 28 and 371 days. The results, for the most part, were satisfactory, since at the age of 371 days all blocks met the normative requirements, making their manufacture and commercialization theoretically possible. It is worth noting that there are still no ABNT standards for the manufacture of concrete blocks with recycled or artificial aggregates, so in this study the NBR 6136

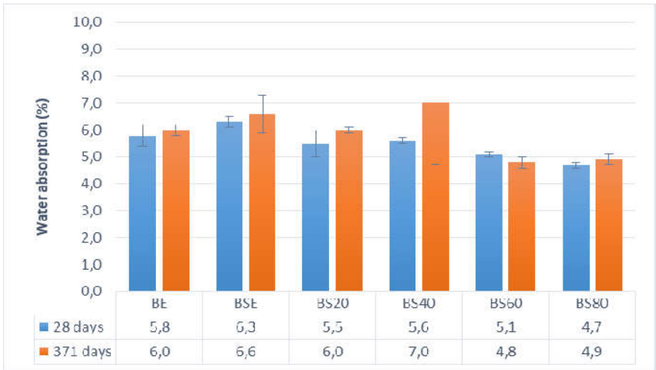


Figure 8. Result of the water absorption tests
Source: Authors (2021)

The net area of the blocks tested corresponded to 51% in relation to the gross area, meeting the normative requirement that prescribes that this ratio should be less than or equal to 75%.

Resistance to compression: According to NBR 6136 (ABNT, 2016), for the block studied, the characteristic axial compressive strength should be greater than or equal to 3 MPa at 28 days. Most of the blocks met the normative requirement, with the exception of BS80, which for this age showed a characteristic strength of 2.8 MPa, but with a standard deviation of 0.4 MPa, i.e., strength ranging from 2.4 to 3.2 MPa. For test results at older ages, 371 days, all blocks met the minimum strength, especially the BS40 block, which showed the highest compressive strength in relation to the other blocks. In Figure 9 it is possible to observe the results of compressive strength tests for ages 28 and 371 days.

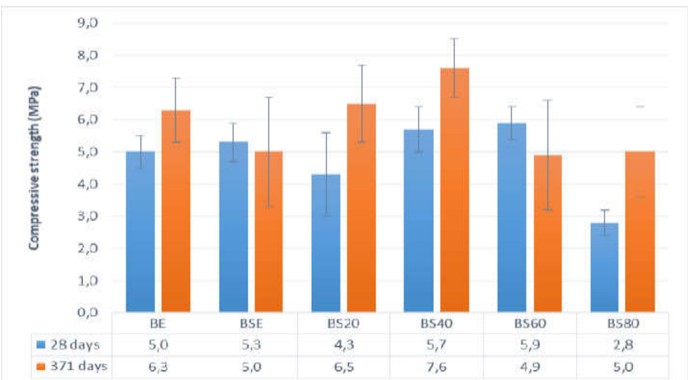


Figure 9. Results of the compressive strength tests
Source: Authors (2021).

Comparing the results of the reference block with the others, tested at 28 days of age, according to the Brazilian norm, we have: BE 5.66%

mandatory effect in Brazil, i.e., a standard is not a law, but by force of law, they must be complied with. That said, the results obtained are discussed below. In the dimensional analysis tests, it is highlighted that the BE block, with age of 371 days, presented a height variation of 4 mm in relation to the nominal dimension, exceeding the normative tolerance by 1 mm. This fact is due to the lack of calibration of the vibropress machine at the time of manufacturing the block. However, it does not interfere in the results of the research, since the BE block does not present substitution of natural aggregates by steel slag and is not used as a reference. For the length, in relation to the nominal dimension, the BS40 block with 28 days and the other blocks with age of 371 days, presented dimension of 394 mm, exceeding in 1 mm the normative tolerance. This problem has cause in the wear of the form where the blocks are manufactured, having no relation with the expansibility of the blocks, since it presented this dimension in the BS40 block with 28 days and also in all blocks with age of 371 days, including blocks without replacement of natural aggregates by steel slag, which is the case of BE and BSE blocks. As for the water absorption tests, all blocks met the normative requirement presenting individual absorption lower than 11% and, on average, lower than 10%. There was a tendency to increase the absorption of the blocks tested with 371 days in relation to the 28 days blocks. The standard deviation of the BS40 block was very high, showing great oscillation in the result. A statistic analysis was performed, through the ANOVA method of the results of the two ages and it was proven that the differences are not statistically significant, i.e., all results are equivalent. In the compressive strength tests, only the BS80 block at age 28 days did not meet the minimum strength required by standard, but it was very close, so that considering the standard deviation, the block could meet this requirement. At 371 days the BS80 block presented resistance of 5.0 MPa, exceeding in 67% the minimum required and 78% the reached in the previous test. In the results of 371 days of age, all blocks met the minimum required strength with highlight for the BS40 block that showed resistance of 7.6 MPa, exceeding in 153% the minimum strength recommended in the standard and having an increase of 33% compared to the first test. As the standard analyzes the results for age 28 days, the BS60 block was the one that presented the best result for this age. A statistical analysis of the results was performed using the ANOVA method, comparing the two ages tested and it was obtained that the differences found are not statistically significant and, therefore, the results are equivalent. In general, the results were satisfactory, since the BS20, BS40 and BS60 concrete blocks, with replacement of natural aggregates by artificial aggregates from BSSF steel slag, met the requirements of NBR 6136 (ABNT, 2016). The finishing of the blocks was not studied in this work, but it is worth noting that with adjustment of the granulometric compositions, this factor can be improved, especially in blocks with higher replacement content. At the time of manufacturing, the BS80 block remained cohesive, but less so than the others, presenting a very rough surface and less interlocking of the particles. In Figure 10 it is possible to observe the difference in the finishing of the blocks, being the BSE block smoother and those with replacement, rougher.

Source: Authors (2020)

After systematic review of the literature, no published work was found with the use of BSSF steel slag for the manufacture of concrete blocks, which makes this work unprecedented. What exists in the literature are researches that used BSSF steel slag to produce concrete and mortar or even studies that manufactured concrete blocks with ordinary steel slag, with old processing and waiting for a long period of curing time for stabilization. Dias et al. (2020) studied the production of concrete with partial replacement of Portland cement by BSSF and analyzed the physical and mechanical properties of concrete, with replacements of 3, 6 and 12%. The best result for compressive strength at 28 days was with 12% replacement, where there was an 18% increase over the reference concrete without replacement. As for water absorption, the lowest value found was for the 12% replacement, with a 20% reduction in relation to the reference concrete. The BSSF steel slag used by the authors originated from the same steel mill as the one used in the present study. When analyzing the expansibility, according to NBR 16697 (ABNT, 2018) the slag did not present cold expansion and was within the maximum limit for hot expansion. Santos (2014) produced a concrete block with total replacement of natural aggregates by artificial aggregates from electric steel slag. In his study, the slag block showed water absorption of 4.1% and compressive strength of 13.08 MPa, while the natural block obtained water absorption of 7.9% and compressive strength of 11.13 MPa, both at 28 days, i.e., 48% reduction in water absorption and increase in compressive strength of 17.52%. Therefore, the block with slag showed less water absorption and higher compressive strength. The results obtained in this study followed the same line of other authors who study the same subject, i.e., the use of BSSF steel slag provides an increase in compressive strength, reduced water absorption and does not interfere in the dimensions of the blocks.

CONCLUSION

With test results at ages 28 days, according to the normative reference, and at an advanced age of 371 days, it was confirmed the technical feasibility of production and commercial use of concrete blocks, without structural function, with partial replacement of natural aggregates by artificial aggregates, from BSSF steel slag. According to the results obtained in this research, the blocks with 60% replacement showed better results of compressive strength at 28 days, besides meeting the other requirements of NBR 6136 (ABNT, 2016) regarding dimensional analysis, water absorption and net area. For this replacement, the blocks exceeded by 97% the minimum strength recommended in the standard for the type of block produced.

In the results of durability, with tests at the age of 371 days, the blocks with 40% substitution obtained better results of resistance to compression, but when compared to the others, did not show significant differences in statistical analysis. In relation to the mass of the blocks, an increase was already expected in the blocks with higher levels of substitution, since the BSSF steel slag is denser than the natural aggregates, but this increase was not exaggerated, since the BS60 was 9% denser than the BSE (reference) in contrast 11.3% more resistant. As for the finish of the blocks with replacement, it was not object of the study, but it is clear that with granulometric adjustment in the concrete mix, it is possible to correct this aspect, besides achieving greater interlocking of the particles, contributing to a reduction in porosity and gain in technical quality. With the confirmation of the resistance gain, when BSSF steel slag is used in the block composition, it is proposed to advance in the studies to adjust the mix, with a reduction of binder, in order to meet the normative requirements and provide cement savings per m3 of concrete. Thus, contributing to the reduction of greenhouse gases, in addition to reducing the production costs of the blocks. Therefore, it was possible to conclude that the results obtained have great relevance for the sustainable development of the waste generating region, since the material studied can generate a new life cycle for steel slag, as well as reduce the environmental impacts caused by this

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