Evaluation of mortars produced with Baosteel slag short flow (BSSF) steel slag as fine aggregate

F. A. Amancio[1], A. R. O. Dias[1], D. A. Lima[1], A. E. B. Cabral[1], E. F. T. Mesquita[2]*
[1]*Universidade Federal do Ceará, Departamento de Engenharia Estrutural e Construção Civil, 60455-900, Fortaleza, CE, Brazil*
[2]*Universidade Federal do Ceará, Laboratório de Reabilitação e Durabilidade das Construções, Russas, CE, Brazil*

Abstract

The objective was to evaluate the influence of Baosteel slag short flow (BSSF) steel slag, a byproduct of a Brazilian steel mill, as a fine aggregate on the properties of fresh state and on the compressive strength of mortars. The experimental work was to characterize the BSSF steel slag and to produce simple mortars (only cement) and mixed mortars (cement and lime), replacing the natural sand with the slag aggregate in 20%, 40%, and 60% by volume. The fresh state tests were specific mass, incorporated air, water retention, and squeeze-flow, while in the hardened state, compressive strength at 28 days was investigated. It was verified that mortars with higher slag contents required greater amounts of water to obtain the spread (consistency) on the flow table, which was fixed at 260±5 mm. The mortars with slag presented higher specific mass since the slag had a higher density than natural sand and less water retention in the case of simple mortars. In addition, it was verified that the mortars with BSSF steel slag presented lower values of maximum displacement in the squeeze-flow test, which negatively affected its workability in the fresh state, besides the properties of mortar adherence. In addition, it was verified through the analysis of variance that the substitution of natural sand by BBSF steel slag did not significantly influence the compression strength of mortars.
Keywords: steel slag, BSSF, rendering mortar, squeeze-flow.

INTRODUCTION

Natural resource consumption has increased, following the population growth, as well as the development of the economic sectors, causing great impacts on the environment. In this scenario, the industry of civil construction has a prominent role, given that it is one of the largest consumers of non-renewable natural resources. As an example, in 2017, this sector consumed 497 million tons of aggregates [1]. As one of the main inputs for construction, the natural aggregate exploration, which are used in mortars and concrete production, causes countless impacts to the environment, either because of a disordered extraction (and often illegal) or because 90% of the national production of natural sand is obtained from the extraction of river beds and the remaining 10% from other sources, such as floodplains, lake deposits, and others [2]. The rapid extraction of natural aggregates from the riverbed has caused numerous environmental impacts, such as the deepening of riverbeds, loss of vegetation on the banks of rivers, disruption to aquatic life, in addition to impacts on agriculture, due to the reduction of the level of the water table [3].

In parallel, there is a prominent role in the steel industry in Brazil's and the world's economy and environment. Steel production in 2017 reached a new record, totaling 1.7 billion tons [4]. However, a large amount of steel slag is generated by the steel industry, which represents an increase in the cost of disposing of this waste [5, 6], and it is estimated that the steel slag generation can reach 1 ton for every 3 tons of steel produced [7, 8]; in Brazil, the estimate is 5.6 million tons per year. Therefore, as steel production increases, the amount of waste generated becomes an environmental problem that needs urgent treatment, and it is essential for future generations that these materials are considered resources to be reused [9]. Thus, there is a need to find a suitable destination for these slags, reinserting them in new production processes. It must also be considered that the simple disposal of this waste generates costs of transportation, storage, and final disposal [6, 10, 11]. Moreover, several studies have demonstrated that steel slag has good physical characteristics, such as high strength and durability, which shows a potential to be used as aggregates in the construction industry [12, 13]. Consequently, the use of industrial byproducts by the construction industry can contribute to solve problems of lack of aggregates in several locations and reduce environmental problems related to mining [14]. So, the civil construction sector is one of the industries that are most interested in the use of this type of waste and seeks to incorporate it in construction materials, aiming to improve the properties of its products, reduce production costs, and generate less environmental impact.

Steel slag contains hydratable oxides (free CaO and/or free MgO) that can result in volumetric instability, causing expansion [9, 13, 15]. However, the steel slag from Companhia Siderúrgica do Pecém, located in the State of Ceará, Brazil, undergoes a treatment process, where the

*felipeaamancio@hotmail.com
https://orcid.org/0000-0002-1349-683X

liquid slag is swiveled on a rotating drum, being cooled quickly with water jets, combined with mechanical forces for crushing, forming a glassy, granular material with low amounts of free lime [16-18]. Thus, there is the generation of Baosteel slag short flow (BSSF) steel slag, a material free of expansion [16, 17]. However, most research has focused on investigating the mechanical and durability of mortars and concrete with the incorporation of steel slag [19-22]. In this sense, the objective of this work is to investigate the influence of natural fine aggregate substitution by Baosteel slag short flow (BSSF) steel slag in the properties of fresh state and the compressive strength of simple and mixed mortars.

MATERIALS AND METHODS

Materials: Portland cement CP V-ARI was used. The water used came from the water supply system of the city of Fortaleza, Brazil. The lime used was the hydrated lime type CH-I, with a specific mass of around 2.56 g/cm^3. The sand used was natural, from the Metropolitan Region of Fortaleza, Brazil, while the steel slag used was BSSF, made available by the steel mill Companhia Siderúrgica do Pecém (CSP), located in São Gonçalo do Amarante, Ceará, Brazil. The slag was dried in an oven (105±5 °C) until mass constancy. After drying, it was sieved, following the NBR NM 248 standard [23]. According to an analysis carried out by Souza [18], using scanning electron microscopy (SEM), it was observed that the slag from the BSSF steel slag had a rough surface and characteristics that the material was formed from a molten and agglomerated material, not being able to form well-defined crystalline structures. This agglomeration was due to the fact that the BSSF steel slag originated from a process of fusion of materials of very different chemical compositions, as well as by the presence of magnetite since this magnetic phase causes agglomeration and hinders the analysis by SEM. Then, the adjustment of the granulometric distribution of the slag was carried out to match that of the natural sand in order to avoid the influence of the grain size on the workability and other properties of the mortars. Fine aggregates met the requirements of the NBR 7211 standard [24], and their characteristics are shown in Table I.

The shape of the aggregate grains was verified using the aggregate image measurement system (AIMS). It was possible to verify that natural sand tended to have more rounded particles than BSSF steel slag, which was predominantly angular, in addition to a more polished texture, whereas the steel slag had a texture with low roughness, according to Al Rousan's classification [29]. Regarding the chemical characterization of steel slag, the X-ray fluorescence (XRF) was performed in a spectrometer (ZSX Mini II, Rigaku). The results in Table II show that the slag was basically made up of Fe_2O_3 and CaO (>88%). The expandability in BSSF steel slag was also investigated, based on the cement expansion determination test by the Le Chatelier method, according to NBR 11582 standard [30]. For this method, a cement substitution content of 50% by volume of BSSF steel slag was adopted. It has been reported that this content is enough for the phenomenon to occur if the material has expansive characteristics [31]. It is noteworthy that it did not show cold expansion and, in relation to the hot expansion, all the results obtained were less than 5 mm.

Methods of mortar preparation and characterization: simple mortars (cement-based binder) and mixed mortars (cement and lime) were prepared. The reference mixes of simple mortars had cement:fine aggregate ratios of 1:3, 1:5, and 1:7, and those of mixed mortars had cement:fine aggregate:lime ratios of 1:4:1, 1:6:1, and 1:8:1. The mixes are presented in mass combined with volume. For example, the 1:6:1 mix consisted of 1 bag (50 kg) of cement, 6 recipients (40 L) of wet sand, and 1 bag (20 kg) of lime. These mixes were transformed into mass by means of the unitary mass of the aggregates in order to facilitate the production. It is noteworthy that the definition of the mixes started from the proportions 1:5 and 1:6:1 because they are often found in the literature and used by some construction companies in the city of Fortaleza, Ceará, Brazil. From these mixes, two variations were obtained, one richer (with a greater amount of binder) and the other poorer, obtaining the mixes previously described. The consistency index was measured by the flow table test fixed at 260±5 mm, according to NBR 13276 standard [32]. From this index, the amount of water for each mix was determined. The substitution of natural sand by BSSF steel slag occurred in volume, with substitution contents of 20%, 40%, and 60%, in addition to a reference mix, without the use of BSSF steel slag. The contents were

Table I - Physical characteristics of the aggregates.

Test	ABNT standard	Unit	Sand	Slag
DMC	NM 248 [23]	mm	2.36	2.36
Fineness module	NM 248 [23]	-	2.52	2.52
Unit mass	NBR NM 45 [25]	g/cm^3	1.41	2.08
Water absorption	NBR NM 52 [26]	%	0.9	2.1
Specific mass	NBR NM 52 [26]	g/cm^3	2.59	3.86
Content of particles <75 μm	NBR NM 46 [27]	%	1.0	1.3
AAR	NBR 15577-4 [28]	%	-	0

DMC: maximum aggregate size; AAR: alkali-aggregate reactivity.

Table II - Chemical composition (wt%) of Baosteel slag short flow (BSSF) steel slag.

Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	Co_2O_3
0.63	5.84	1.01	0.04	33.46	0.63	0.21	5.09	52.98	0.12

Table III - Mix proportions of tested mortars.

Mix	ID	Material consumption (kg/m^3)					Unit mix in mass					Water content (%)
		Cement	Slag	Sand	Lime	Water	Cement	Slag	Sand	Lime	w/c	
1:3	REFA	570.1	0	1339.7	0	296.4	1	0	2.35	0	0.52	13.4
	A20	563.7	394.6	1059.7	0	304.4	1	0.70	1.88	0	0.54	13.1
	A40	557.4	780.4	786.0	0	312.2	1	1.40	1.41	0	0.56	12.8
	A60	560.6	1177.3	527.0	0	308.3	1	2.10	0.94	0	0.55	12.0
1:5	REFB	374.5	0	1468.0	0	310.8	1	0	3.92	0	0.83	14.4
	B20	372.0	435.2	1164.3	0	316.2	1	1.17	3.13	0	0.85	13.8
	B40	368.0	857.3	864.7	0	323.8	1	2.33	2.35	0	0.88	13.4
	B60	365.0	1277.5	573.1	0	328.5	1	3.50	1.57	0	0.90	12.9
1:7	REFC	275.3	0	1508.5	0	327.6	1	0	5.48	0	1.19	15.5
	C20	271.4	442.4	1191.6	0	336.6	1	1.63	4.39	0	1.24	15.0
	C40	265.0	866.4	871.7	0	352.4	1	3.27	3.29	0	1.33	15.0
	C60	265.8	1302.6	582.2	0	350.9	1	4.90	2.19	0	1.32	14.0
1:4:1	REFD	403.0	0	1261.3	161.2	318.4	1	0	3.13	0.40	0.79	14.9
	D20	401.1	373.0	1006.8	160.4	320.9	1	0.93	2.51	0.40	0.80	14.2
	D40	399.5	747.0	751.0	159.8	323.6	1	1.87	1.88	0.40	0.81	13.6
	D60	401.4	1124.0	501.8	160.6	321.1	1	2.80	1.25	0.40	0.80	12.8
1:6:1	REFE	296.9	0	1395.6	118.8	317.7	1	0	4.70	0.40	1.07	14.9
	E20	296.1	414.5	1113.3	118.4	319.8	1	1.40	3.76	0.40	1.08	14.1
	E40	294.4	824.2	830.1	117.7	323.8	1	2.80	2.82	0.40	1.10	13.5
	E60	295.2	1240.0	555.1	118.1	321.8	1	4.20	1.88	0.40	1.09	12.7
1:8:1	REFF	233.4	0	1463.6	93.4	322.1	1	0	6.27	0.40	1.38	15.2
	F20	231.9	433.7	1161.9	92.8	327.0	1	1.87	5.01	0.40	1.41	14.6
	F40	229.7	859.0	863.6	91.9	333.1	1	3.74	3.76	0.40	1.45	14.0
	F60	224.1	1254.8	562.4	89.6	349.5	1	5.60	2.51	0.40	1.56	14.1

defined after preliminary tests, whereby it was found that for contents above 80% substitution, the mortars had low workability. Table III shows the proportions of the mixes produced, with water consumption defined according to NBR 13276 standard [32].

After determining the mixes, the mortars were prepared following the procedures recommended by the NBR 16541 standard [33]. Then, the characterization of mortars in the fresh state was carried out. For determining the specific mass and the incorporated air content, the gravimetric method described in the NBR 13278 standard [34] was used. The water retention test was performed according to the NBR 13277 standard [35]. To investigate the rheological behavior of mortars, the squeeze-flow test described in the NBR 15839 standard [36] was used. Finally, the compressive strength of mortars was determined, as recommended by NBR 13279 standard [37], which was carried out in 3 samples for each condition, totaling 72 specimens. Three repetitions for each trial and statistical analysis of the results, using the analysis of variance (ANOVA) with a 95% confidence level using the Statistica 7.0 software, were performed.

RESULTS AND DISCUSSION

Table IV shows a summary of the results obtained in the characterization tests of fresh mortars. Next, the discussions for each property evaluated are presented.

Table IV - Characterization results of fresh mortars.

Mix	Slag content	w/c	Flow table (mm)	Spec. mass (kg/m^3)			Air content (%)			Water retention (%)			Max. displ. squeeze-flow at 3 mm/s (mm)		
				1	2	3	1	2	3	1	2	3	1	2	3
1:3	0%	0.52	258	2165	2160	2162	3	3	4	88	89	90	2.36	2.64	2.86
	20%	0.54	263	2294	2306	2290	1	1	2	87	84	84	2.07	2.31	2.52
	40%	0.56	258	2392	2400	2393	2	1	2	85	84	83	2.90	2.71	2.62
	60%	0.55	260	2533	2517	2523	2	2	2	88	85	87	2.56	2.11	2.21
1:5	0%	0.83	259	2062	2072	2067	4	4	4	86	87	87	1.51	1.65	1.42
	20%	0.85	258	2207	2205	2206	3	4	3	89	85	86	1.64	1.45	1.91
	40%	0.88	263	2315	2316	2317	4	4	4	88	82	84	1.73	0.75	0.98
	60%	0.90	260	2463	2454	2457	3	4	3	84	82	82	1.35	1.21	1.33
1:7	0%	1.19	262	2035	2027	2031	4	4	4	85	81	83	1.31	1.36	1.49
	20%	1.24	259	2118	2141	2123	6	5	5	86	82	83	1.19	0.84	1.84
	40%	1.33	256	2273	2272	2274	4	4	4	81	83	80	1.61	1.32	1.49
	60%	1.32	261	2399	2424	2418	4	3	3	84	80	81	1.04	1.29	1.10
1:4:1	0%	0.79	261	2096	2105	2099	2	2	2	92	90	90	4.66	4.10	5.01
	20%	0.80	260	2230	2232	2228	2	1	2	92	88	89	4.17	4.10	4.50
	40%	0.81	262	2325	2328	2326	2	2	2	90	87	87	4.66	4.35	4.50
	60%	0.80	264	2412	2432	2427	4	3	3	87	87	88	3.67	3.80	3.92
1:6:1	0%	1.07	257	2045	2063	2051	4	3	4	91	89	87	1.75	2.61	2.31
	20%	1.08	264	2202	2194	2181	3	3	4	85	84	90	1.81	2.40	1.66
	40%	1.10	258	2316	2339	2312	3	2	3	84	82	86	2.35	1.71	2.01
	60%	1.09	262	2445	2442	2442	3	4	4	88	82	83	1.41	1.96	1.96
1:8:1	0%	1.38	258	2012	2031	2018	5	4	4	83	85	89	2.06	1.92	2.27
	20%	1.41	263	2151	2143	2133	4	5	5	90	84	87	1.21	1.47	1.39
	40%	1.45	258	2262	2273	2263	5	4	5	89	86	85	1.22	0.83	1.04
	60%	1.56	263	2374	2393	2387	4	4	4	88	86	84	1.41	1.34	1.32

Water-cement (w/c) ratio: Figs. 1a and 1b show the correlation between the w/c ratio of simple and mixed mortars, respectively, and the substitution content of natural sand by steel slag. It is important to remember that the mortar consistency was fixed at 260±5 mm. As can be seen in Fig. 1, mortars with higher slag contents showed a higher w/c ratio, i.e., as the natural fine aggregate was substituted by steel slag sand, there was a greater need for water in the mixture. The higher demand for water in slag mortars can be justified by the higher water absorption of slag when compared to natural sand, as well as by the difference in the slag particle shape and texture when compared to that of natural sand. The rougher texture of the slag compared to that of natural sand demanded a greater amount of paste to maintain the same workability, thus increasing the amount of water and also increasing the w/c ratio. The same fact was verified by Silva et al. [21], with an increase of w/c ratio in mixed mortars. It should also be noted that for the 1:3, 1:7, 1:1:4, and 1:1:6 mixes, the w/c ratio for the 60% substitution content was lower than that found in the content of 40%, despite being practically equivalent values. This can be justified by the increase in specific mass since with the drops of the flow table, the heavier (denser) mortar tends to spread more [38]. Bearing in mind that the specific mass of the slag (3.86 kg/m^3) was higher than that of natural sand (2.59 kg/m^3), it is explained, therefore, that the specific mass of the mortars with slag favored the spreading in the flow table. This test, therefore, was not the most suitable to measure the consistency of mortars with slag. It was noticed that mixed mortars had a higher w/c ratio than simple mortars; this was due to the fact that lime has much finer grains than cement, that is, a larger surface area, thus requiring a greater amount of water. In the same sense, it has been explained [39] that the lime, when incorporated in mortars, requires an increase in water demand to maintain the same consistency. This additional water, which is not consumed by cement hydration, remains free in the system and, when evaporating, results in greater porosity of the hardened mortar.

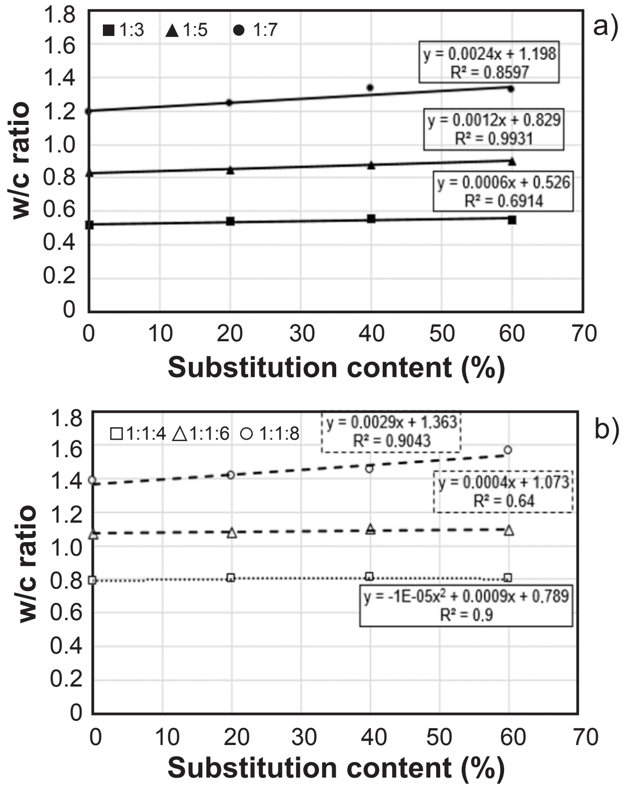

Figure 1: Correlation between water/cement (w/c) ratio and slag content in mortars.

Regarding the variation of the mixes tested, it was noted that mixes with a higher content of binders required less w/c ratio to achieve the same consistency (Fig. 2). This fact was also verified by Mattos et al. [40], who explain that the increase in cement content causes an increase in workability due to the increase in the amount of paste in the system and the consequent covering of aggregates by the paste. This positively influences the spreading of mortars. According to Silva et al. [41], the ease with which the mortar is spread is fundamentally related to the phenomenon of movement and lubrication existing between its internal particles.

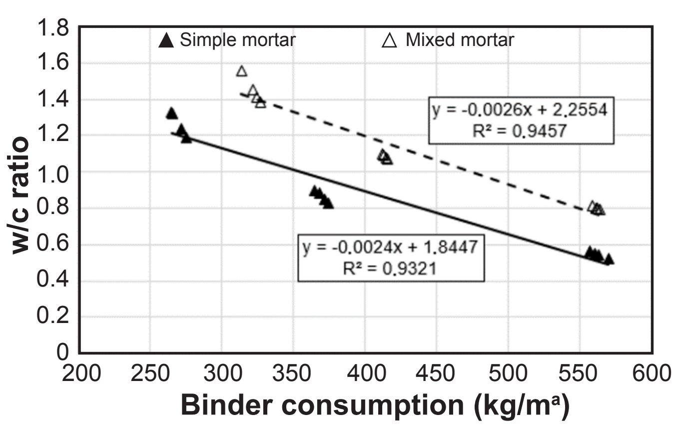

Figure 2: Correlation between water/cement (w/c) ratio and consumption of binder in mortars.

Specific mass: Fig. 3 shows the behavior of the specific mass of the mortars when varying the mix and the

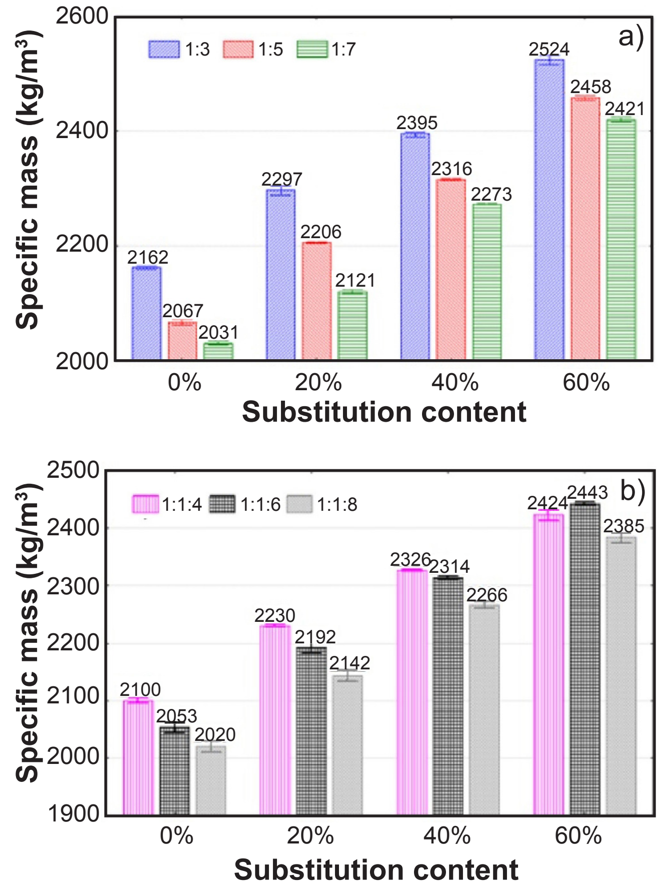

Figure 3: Specific mass of simple mortars (a), and mixed mortars (b).

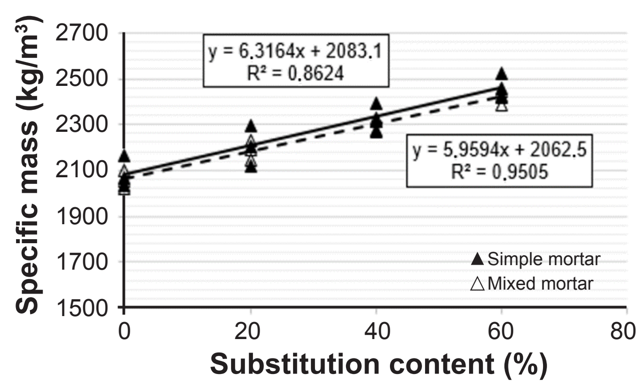

Figure 4: Correlation between the specific mass of mortars and the slag substitution content.

substitution content of sand per slag. As can be seen in Fig. 4, there was a significant increase in specific mass with an increase in the amount of steel slag for all investigated mixes; it was possible to establish a linear correlation with a coefficient of determination (R^2) greater than 0.85. This was due to the higher specific mass of the steel slag (3.86 g/cm^3) when compared to that of natural sand (2.59 g/cm^3). The same behavior was observed before [42, 43]. In addition, regarding the difference in specific mass among the mixes, those with the highest consumption of binder presented the highest specific mass since the specific mass of cement is higher than that of natural sand. The specific mass of mortars

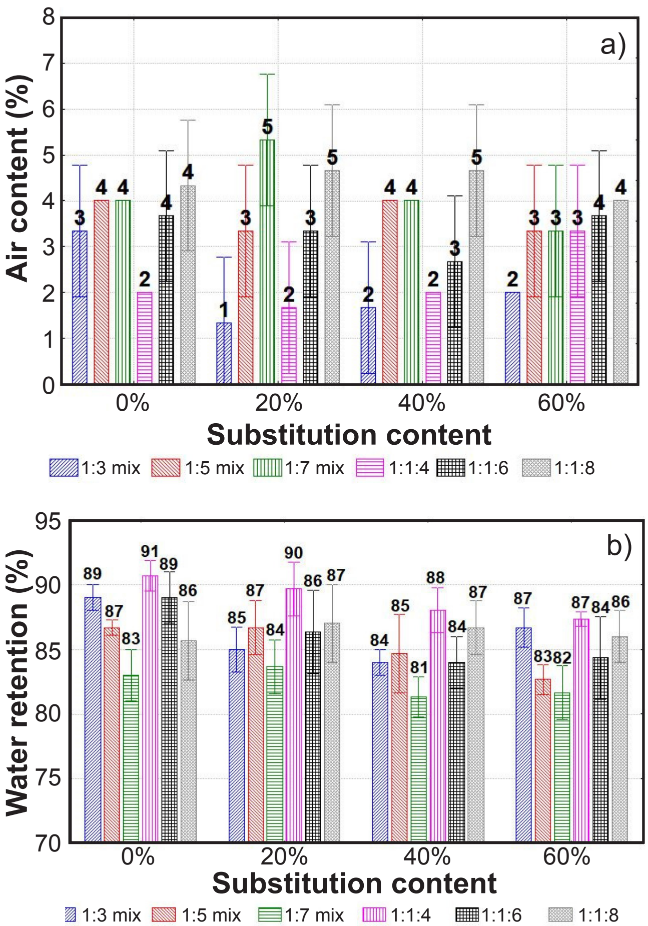

Figure 5: Air content (a) and water retention (b) of mortars.

is directly related to their workability; that is, lighter mortars make it possible to reduce the effort during their application, resulting in greater productivity of the worker [44]. Thus, mortars with BSSF steel slag as they are heavier tend to negatively affect worker productivity. According to ABNT NBR 13281 standard [45], all the mortars investigated were classified as D6 (specific mass >2000 kg/m^3). However, the classification of mortars according to the specific mass proposed by Carasek [46] establishes that specific masses between 1.40 to 2.30 g/cm^3 are classified as normal, while those greater than 2.30 g/cm^3 are classified as heavy. Thus, for the BSSF steel slag investigated, mortars with a content of 60% substitution of natural sand by slag are classified as heavy mortars.

Incorporated air: regarding the air content in mortars, ANOVA showed that the substitution content did not significantly influence this property; in addition, it was not possible to observe any tendency in the air content with the substitution content of the natural sand by steel slag. Fig. 5a shows that the poorest mixes had higher values of incorporated air content. This can be justified by the increase in the w/c ratio, as well as the increase in the aggregate content, causing an increase in the air content. On the other hand, the increase in the cement content causes a reduction in the incorporated air content in cementitious materials [47]. This increase results in a better packaging of mortars, and consequently, there is less free space for bubbles to form [48]. It should also be noted that the values of incorporated air content were low (Fig. 5a) because additives were not used. For simple or mixed mortars produced without additives, the air content is generally around 2% to 5% of the total volume [49]. It has been explained that this value corresponds to the trapped air, whose air bubbles are irregular and not stable, resulting from trapping during mixing, while the incorporated air is stable air bubbles with the appearance of microscopic spheres, resulting from the use of additives [49].

Water retention: for mixes without lime, according to ANOVA, it was observed that the substitution content significantly influenced water retention in simple mortars, but not in mixed mortars (Fig. 5b). The reduction in water retention in simple mortars can possibly be justified by the higher w/c ratio of mortars with slag due to the fact that mortars become less water retainer when the proportion of binder water is increased [50]. This did not happen in mixed mortars, possibly due to the presence of lime and its high water retention capacity. It is also noteworthy that the values obtained for water retention were between 80% and 90% for the investigated mixes. This property prevents the rapid suction of water by the substrate and also the water evaporation due to bad weather, which favors the coating durability. In addition, it is seen that the rapid loss of water from the mortar affects its adhesion, mechanical resistance, ability to absorb deformations and consequently causes loss of durability and tightness [51]. Also, according to Fig. 5b, the high water retention values can be seen for the 1:3 mix, similar to those obtained for the mixes with lime, possibly due to the high specific area of cement compared to that of sand. It has been found that mortars with a 1:3 ratio have the same water retention capacity as ratios with lime, such as 1:1:6 and 1:2:9 [52]. Also, according to the classification of mortars based on water retention (NBR 13281 standard), it was found that, with the exception of the 1:1:4 ratio, the other mixes were between U4 and U3 class. Although there was a weak tendency to reduce water retention with the increase in the substitution content of natural sand by BSSF steel slag, it was not possible to establish a correlation between such parameters.

Squeeze-flow: regarding the squeeze-flow, the test was carried out 3 times for the squeezing speed of 3 mm/s in order to verify the influence of the BSSF steel slag on the mortar rheology using ANOVA. With the squeeze-flow graphs, maximum displacements were obtained (Table IV); besides, the test was also carried out for the speed of 0.1 mm/s in order to compare the behavior of mortars at different displacement rates. It should be noted that these speeds are recommended by the NBR 15839 standard [36]. The results of the squeeze-flow test for the speeds of 3 and 0.1 mm/s are shown in Figs. 6 and 7. The results of the maximum displacement at the displacement rate of 3 mm/s are shown in Table IV. The load-displacement curves showed a change from an elastic stage directly to the strain hardening stage, phase III, in which the load increased considerably with a small increase in deformation. The second stage, related to the plastic deformation of the material, was absent, with the exception of the 1:1:4 mix that presented a beginning of plastic deformation or viscous flow; however, this behavior was not very significant. In the second stage, the mortar is capable of undergoing deformations without a significant increase in stress, which makes it suitable for applying and spreading [53]. It was observed that, for the water content defined as the consistency index fixed at 260±5 mm, according to NBR 13276 standard [32], for the maximum test load of 1 kN, the displacement was below 3 mm for all mortars (with the exception of the 1:1:4 mix due to a large amount of binder). This demonstrated the high consistency of mortars, which were not very suitable for the application. The use of a greater amount of water, or the use of additives, would assist in lubrication, consequently reducing the compression loads.

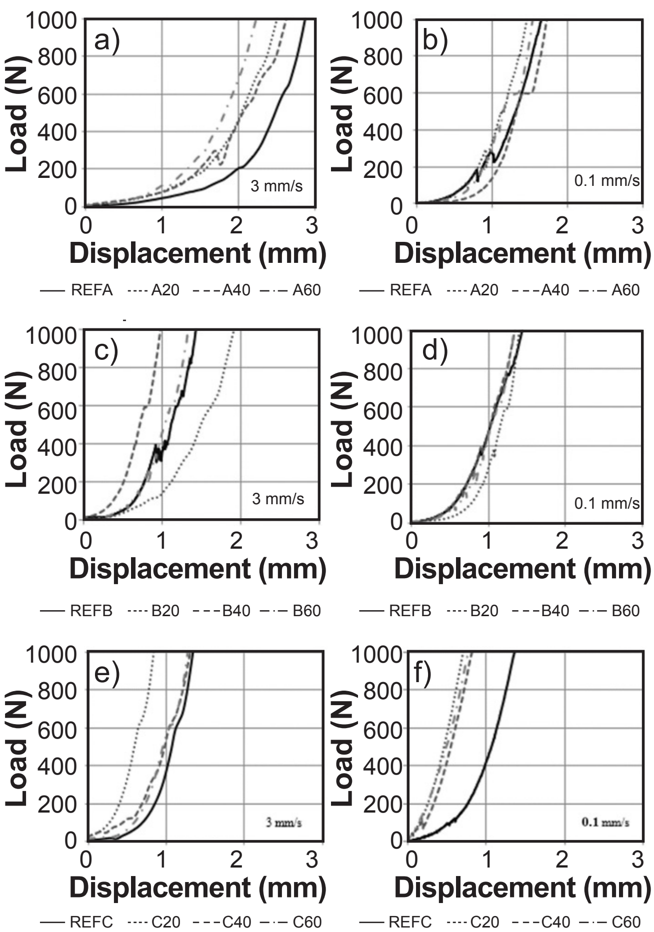

Figure 6: Squeeze-flow behavior of simple mortars with mixes of 1:3 (a,b), 1:5 (c,d), and 1:7 (e,f) at speeds of 3 mm/s (a,c,e) and 0.1 mm/s (b,d,f).

The exponential growth of loads characterizes the stiffening due to deformation, caused by high levels of friction between the aggregates. Due to the low air content in the mortar, the aggregates were very close, making the material flow difficult. On the other hand, increasing the air content in mortars causes an increase in the paste content,

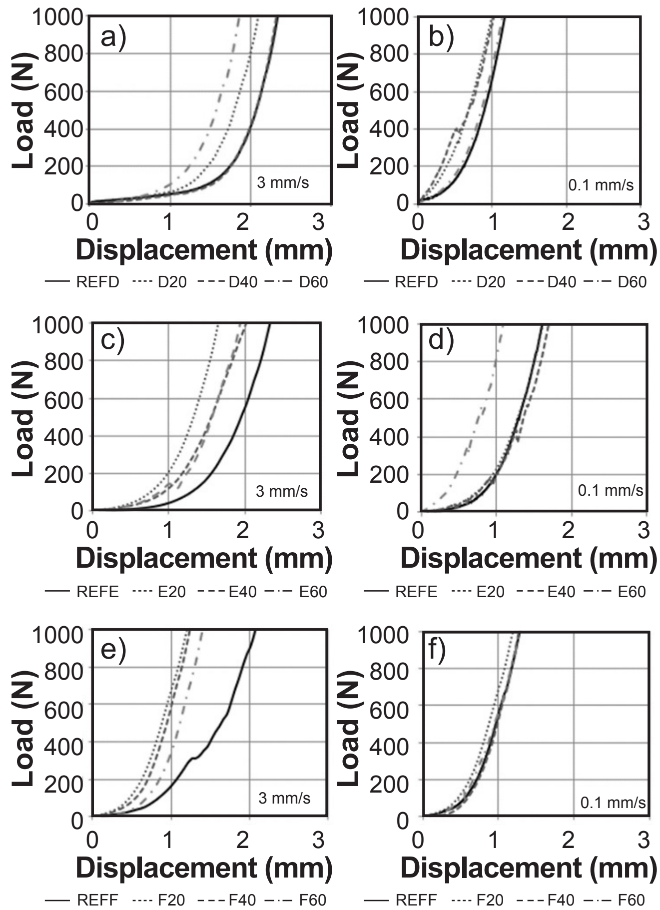

Figure 7: Squeeze-flow behavior of mixed mortars with mixes of 1:1:4 (a,b), 1:1:6 (c,d), and 1:1:8 (e,f) at speeds of 3 mm/s (a,c,e) and 0.1 mm/s (b,d,f).

keeping the aggregates distant and lubricated [54]. As a result, mortars with high air content have a predominantly plastic behavior for the levels of deformation imposed. The air bubbles increase the volume occupied by the paste and reduce its resistance, promoting ease of flow, as well as the slip of the grains [55]. The low displacements found in the squeeze-flow test may be related to the mixing stage, taking into account that França et al. [56] investigated several mixing procedures, including the one recommended by NBR 13276 standard and its influence on the squeeze-flow test. It was found that the standard's mixing procedure, the same adopted in this research, reached lower displacement values when compared with the other procedures, which demonstrates that this procedure was not able to efficiently disperse the agglomerated particles, resulting in larger mobile units (agglomerated), hindering the mortar flow [56]. The results of squeeze-flow for the speed of 0.1 mm/s showed greater resistance to flow, i.e., less displacement than at the speed of 3 mm/s, the same behavior verified by Stolz and Masuero [57]. In this sense, Cardoso et al. [58] explain that mortars are less susceptible to segregate when subjected to higher displacement speeds, which means that they flow more easily. Finally, with the maximum displacement data presented in Table IV, ANOVA was performed for data analysis. It was found that the mix, substitution content, as well as the mix versus substitution content interaction, had a significant influence on the maximum displacement of mortars in the squeeze-flow test. Regarding the mix influence, it is noteworthy that the lime mixes showed the largest displacements due to the increase in plasticity provided by the lime, which positively influenced the spreading capacity of mortars.

Fig. 8 shows the maximum displacements obtained for each investigated mix. Mortars with steel slag, in general, despite the higher w/c ratio, presented lower values of maximum displacements. This can be justified by the slag grain shape (less cubic than the sand) and texture, as well as by the higher water absorption of the slag, leaving less water available for the mixture, and consequently, a lesser amount of paste available to lubricate the grains, thus increasing the friction of the system [59]. This fact demonstrated that the substitution of natural sand by slag negatively affects the rheological properties of mortars, which can negatively influence the properties of the hardened state. As the slag mortars reached the maximum test load (1 kN) with low displacements, this can negatively influence the potential adherence strength of the mortars, due to the reduction of the contact area between the mortar and the substrate. In the same sense, it has been explained that mortars work according to their ability to flow and deform when subjected to certain shearing stress, presenting a more extensive contact with the substrate, optimizing the adhesion mechanism [41]. Although there was a tendency to reduce the maximum displacement with the increase in the substitution content of natural sand by slag, it was not possible to establish a correlation with a high value of the coefficient of determination (R^2).

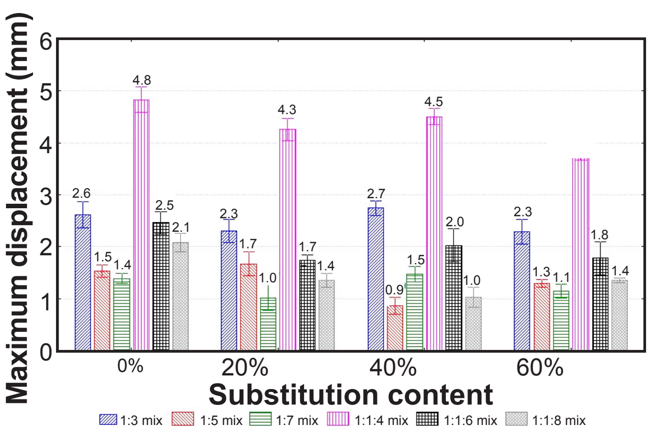

Figure 8: Maximum displacements from the squeeze-flow test (3 mm/s) for the investigated mixes.

Compressive strength: the results of the compressive strength are shown in Fig. 9. According to the analysis of variance, it was found that the substitution content of natural sand by BSSF steel slag did not have a significant influence on the compressive strength of simple and mixed mortars. Although the mortars with BSSF steel slag presented a higher w/c ratio (Table IV), which would favor the reduction of mechanical properties, it can be said that there were overlapping effects due to the shape of the grains and the specific mass of the slag. It should be noted that the test to determine the pozzolanic activity index with Portland cement at 28 days, which was 71%, as well as the chemical characterization of the slag (Table II), combined with the other requirements of NBR 12653 standard [60], indicated that the BSSF steel slag is not a pozzolanic material. As a result, the positive influence of BSSF steel slag on compressive strength was due to the shape of the grains and their specific mass. The more angular grain shape and a rougher texture, as in the case of BSSF steel slag, favor a better interlocking between the particles of the aggregates with the cement paste, thus improving the transition zone [20, 61]. In the same sense, Chen [62] explains

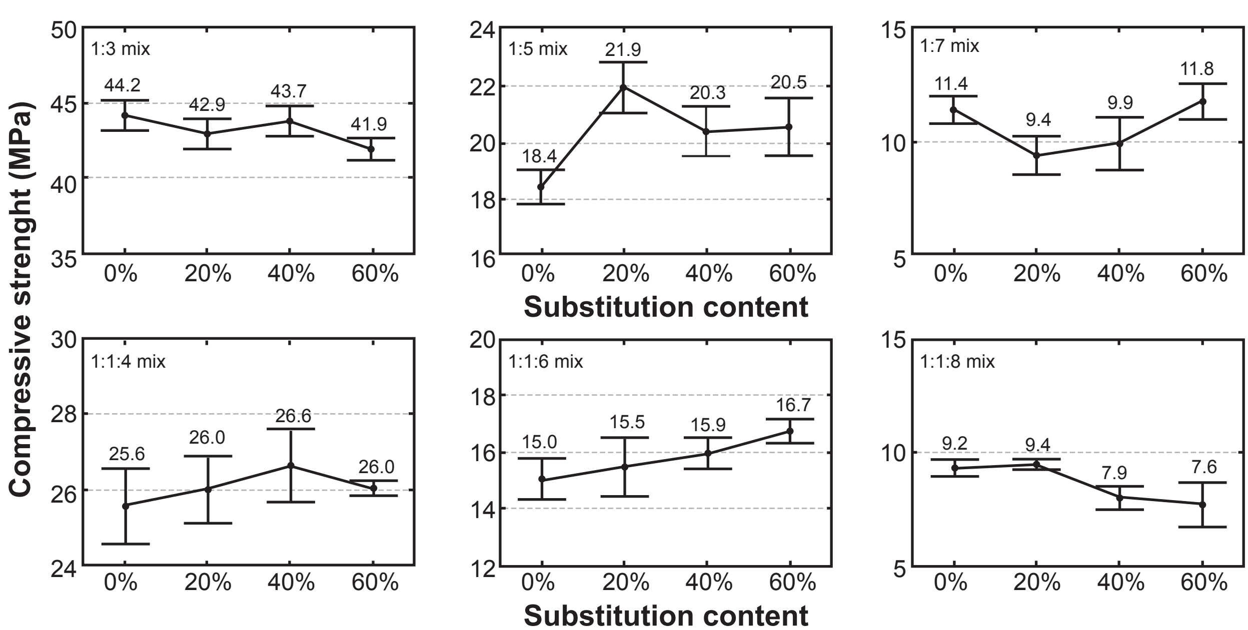

Figure 9: Influence of the mix ratio and substitution content on the compressive strength of the mortars.

that the greater the roughness of the aggregate, the greater the deposition surface of the paste, which improves the particle-paste bonding. In addition, the BSSF steel slag had a specific mass of almost 50% higher than natural sand (Table I). It is also noteworthy that the hardness of the steel slag aggregate is similar or superior to that of aggregates of quartz and granite [63]. Such facts favor the improvement of mechanical properties.

CONCLUSIONS

Regarding the mortars' properties in the fresh state, the substitution of natural sand by Baosteel slag short flow (BSSF) steel slag caused significant changes. Mortars with slag required a larger amount of water to obtain the same consistency. This increase in water was mainly due to the greater water absorption, shape, and texture of grains. With the increase in the substitution of sand by steel slag, there was a gradual increase of the specific mass, reaching 19% for the substitution content of 60%. This was due to the high specific mass and unit mass of the BSSF steel slag compared to natural sand, being almost 50% higher. As a result, mortars produced with the steel slag became denser, which can affect both the quality of the coating and the productivity of the worker. The analysis of variance found that there was no significant difference between the contents of incorporated air for mortars with sand and steel slag. However, the mix ratio had a significant influence on the incorporated air content. The richest mixes presented the lowest values of incorporated air. This was due to the smaller size of the particles when compared to the sand, which favored the filling of the voids, and consequently, the reduction of the air content. In the case of water retention property, while in simple mortars (only cement) the substitution content significantly influenced water retention, reducing the values for mortars with slag due to the higher water/cement (w/c) ratio, in mixed mortars (cement and lime), the analysis of variance identified that the substitution content had no influence on retention, possibly due to the presence of lime and their high water retention capacity. The mixes with the highest content of binders presented higher water retention values; however, it was not possible to obtain a correlation with a high R^2 value. In the case of squeeze-flow, the tested mortars showed low performance of the rheological properties, with the plastic displacement stage present only in the mortars of the 1:1:4 (cement:fine aggregate:lime) mix. The analysis of variance showed that the substitution content and the mix ratio had a significant influence on the maximum displacement by squeeze-flow in the loading of 1 kN of mortars. The richest mixes, as well as those with natural sand (0% substitution), presented the highest displacement values. Regarding the compressive strength, despite the mortar with slag presenting a higher w/c ratio, it was possible to identify that the substitution of natural sand by BSSF steel slag did not have a significant influence on the mechanical resistance. This was due to the high specific mass of the slag, as well as the shape of the grains, whereas denser aggregates, depending on the porosity, tend to generate cementitious composites of greater resistance. Therefore, the substitution of natural sand by BSSF steel slag in coating mortars tends to negatively affect the water retention of Portland cement mortars. In addition, Portland cement mortars and mixed mortars had a rheological behavior by squeeze-flow negatively influenced by the use of BSSF steel slag. The reduction in water retention, as well as the lower performance of rheological properties, can negatively affect the properties of mortars in the hardened state, such as adhesion and durability. Finally, for the use of steel slag in mortars, the behavior of these mortars with the use of air incorporating additives should be investigated, in order to improve the rheological behavior, making them suitable for the application.

REFERENCES

[1] ANEPAC, Rev. Areia Brita **20**, 73 (2018) 34.
[2] S.L.M. Almeida, V.S. Silva, in Proc. Semin. Uso Fração Fina Britagem, EPUSP, S. Paulo (2005).
[3] A.C. Sankh, P.M. Biradar, S.J. Naghathan, M.B. Ishwargol, IOSR J. Mech. Civ. Eng. **11** (2014) 59.
[4] "World steel in figures 2018", World Steel Ass., Belgium (2018).
[5] A. Rodriguez, S. González-Gutiérrez, M. Horgnies, V. Calderón, Mater. Des. **52** (2013) 987.
[6] H. Qasrawi, Constr. Build. Mater. **54** (2014) 298.
[7] H. Shen, E. Forssberg, U. Nordstrom, Resour. Conserv. Recycl. **40** (2004) 245.
[8] B. Das, S. Prakash, P.S.R. Reddy, V.N. Misra, Resour. Conserv. Recycl. **50** (2007) 40.
[9] G. Wang, Y. Wang, Z. Gao, J. Hazard. Mater. **184** (2010) 555.
[10] S. Monosi, M.L. Ruello, D. Sani, Cem. Concr. Compos. **66** (2016) 66.
[11] Z. Chen, J. Xie, Y. Xiao, J. Chen, S.R. Wu, Constr. Build. Mater. **64** (2014) 60.
[12] S.I. Abu-Eishah, A.S. El-Dieb, M.S. Bedir, Constr. Build. Mater. **34** (2012) 249.
[13] G. Wang, Constr. Build. Mater. **24** (2010) 1961.
[14] A.S. Ouda, H.A. Abdel-Gawwad, HBRC J. **13** (2017) 255.
[15] A.S. Brand, J.R. Roesler, Cem. Concr. Compos. **60** (2015) 1.
[16] Y. Liu, X. Wang, Baosteel Techn. Res., Shanghai **5** (2011) 20.
[17] J. Liu, D. Guo, J. Zhu, J. Chen, Baosteel Techn. Res., Shanghai **5** (2011) 15.
[18] T.V.P. Souza, "Caracterização de escória de conversor a oxigênio obtida no processo BSSF antes e após tratamento hidrometalúrgico", M.Sc. Diss., UFC, Fortaleza (2016).
[19] M.S. Guilge, C. Zanetti, A.E.B. Cabral, in Proc. 60th Cong. Bras. Concr., IBRACON, S. Paulo (2018).
[20] A.S. Brand, J.R. Roesler, Cem. Concr. Compos. **86** (2018) 117.
[21] W.K.D. Silva, F.A. Amancio, D.A. Lima, A.R.O. Dias,

A.E.B. Cabral, Rev. Eng. Tecn. **11** (2019) 59.
[22] F.A. Amancio, D.A. Lima, A.R.O. Dias, E.F.T. Mesquita, A.E.B. Cabral, Rev. Matér. **25** (2020) e12562.
[23] NBR NM 248, "Agregados: determinação da composição granulométrica", Ass. Bras. Nor. Técn., Rio Janeiro (2003).
[24] NBR 7211, "Agregados para concreto: especificação", Ass. Bras. Nor. Técn., Rio Janeiro (2009).
[25] NBR NM 45, "Agregados: determinação da massa unitária e do volume de vazios", Ass. Bras. Nor. Técn., Rio Janeiro (2006).
[26] NBR NM 52, "Agregado miúdo: determinação de massa específica e massa específica aparente", Ass. Bras. Nor. Técn., Rio Janeiro (2009).
[27] NBR NM 46, "Agregados: determinação do material fino que passa através da peneira 75 μm, por lavagem", Ass. Bras. Nor. Técn., Rio Janeiro (2003).
[28] NBR 15577-4, "Reatividade álcali-agregado, parte 1: guia para avaliação da reatividade potencial e medidas preventivas para uso de agregados em concreto", Ass. Bras. Nor. Técn., Rio Janeiro (2008).
[29] T.M. Al Rousan, "Characterization of aggregate shape properties using a computer automated system", Dr. Thesis, Texas A&M Un., Texas (2004).
[30] NBR 11582, "Cimento Portland: determinação da expansibilidade Le Chatelier", Ass. Bras. Nor. Técn., Rio Janeiro (2016).
[31] A.B. Masuero, "Estabilização das escórias de aciaria elétrica com vistas a sua utilização como substituição ao cimento", Dr. Thesis, UFRGS, Porto Alegre (2001).
[32] NBR 13276, "Argamassa para assentamento e revestimento de paredes e tetos: determinação do índice de consistência", Ass. Bras. Nor. Técn., Rio Janeiro (2016).
[33] NBR 16541, "Argamassa de assentamento e revestimento de paredes e tetos: preparo da mistura para a realização de ensaios", Ass. Bras. Nor. Técn., Rio Janeiro (2016).
[34] NBR 13278, "Argamassa para assentamento e revestimento de paredes e tetos: determinação da densidade de massa e do teor de ar incorporado", Ass. Bras. Nor. Técn., Rio Janeiro (2005).
[35] NBR 13277, "Argamassa para assentamento e revestimento de paredes e tetos: determinação da retenção de água", Ass. Bras. Nor. Técn., Rio Janeiro (2005).
[36] NBR 15839, "Argamassa de assentamento e revestimento de paredes e tetos: caracterização reológica pelo método squeeze-flow", Ass. Bras. Nor. Técn., Rio Janeiro (2010).
[37] NBR 13279, "Argamassa para assentamento e revestimento de paredes e tetos: determinação da resistência à tração na flexão e à compressão", Ass. Bras. Nor. Técn., Rio Janeiro (2005).
[38] H. Carasek, R.C. Araújo, O. Cascudo, R. Angelim, Rev. Matér. **21** (2016) 714.
[39] V.A. Quarcioni, F.F. Chotolo, S.C. Ângulo, M.S. Guilge, G.R. Cavani, A.L. Castro, M.A. Cincotto, Amb. Constr. **9** (2009) 175.
[40] L.R.S. Mattos, D.C.C. Dal Molin, A.M.P. Carneiro, in Proc. IV Simp. Bras. Tecn. Argam., Brasília (2001).
[41] R.P. Silva, M.M.S.B. Barros, R.G. Pileggi, V.M. John, in Proc. VI Simp. Bras. Tecn. Argam., Florianópolis (2005).
[42] S.A. Campos, M.F.C. Rafael, A.E.B. Cabral, Proc. Struc. Integr. **11** (2018) 145.
[43] A. Santamaria-Vicario, S. Rodrigues, S.G. González, V. Calderón, Constr. Build. Mater. **95** (2015) 197.
[44] C.L.D. Cintra, A.E.M. Paiva, J.B. Baldo, Cerâmica **60**, 353 (2014) 69.
[45] NBR 13281, "Argamassa para assentamento e revestimento de paredes e tetos: requisitos", Ass. Bras. Nor. Técn., Rio Janeiro (2005).
[46] H. Carasek, in "Materiais de construção civil e princípios de ciência e engenharia de materiais", G.C. Isaia (Ed.), IBRACON, S. Paulo (2010).
[47] R.C.O. Romano, "Incorporação de ar em materiais cimentícios aplicados em construção civil", Dr. Thesis, USP, S. Paulo (2013).
[48] N.J.D. Alves, "Avaliação dos aditivos incorporadores de ar em argamassas de revestimento", M.Sc. Diss., UnB, Brasília (2002).
[49] S.W. do Ó, "Análise da retenção de água em argamassas de revestimento aditivadas", M.Sc. Diss., UnB, Brasília (2004).
[50] C. Ince, A. Carter, M.A. Wilson, N.C. Collier, A. El-Turki, R.J. Ball, G.C. Allen, Mater. Struct. **44** (2011) 509.
[51] L.L.M. Baia, F.H. Sabbatini, *Projeto e execução de revestimento de argamassa*, 4th ed., Nome Rosa, S. Paulo (2008).
[52] K.M. Green, M.A. Carter, W.D. Hoff, M.A. Wilson, Cem. Conc. Res. **29** (1999) 1743.
[53] F.A. Cardoso, R.G. Pileggi, V.M. John, in Proc. VI Simp. Bras. Tecn. Argam., Florianópolis (2005).
[54] F.A. Cardoso, F.L. Campora, R.G. Pileggi, V.M. John, in Proc. VII Simp. Bras. Tecn. Argam., Recife (2007).
[55] F.A. Cardoso, R.G. Pileggi, V.M. John, in Proc. VI Simp. Bras. Tecn. Argam., Florianópolis (2005).
[56] M.S. França, F.A. Cardoso, R.G. Pileggi, Amb. Constr. **13** (2013) 111.
[57] C.M. Stolz, A.B. Masuero, Constr. Build. Mater. **177** (2018) 261.
[58] F.A. Cardoso, V.M. John, R.G. Pileggi, Cem. Concr. Res. **39** (2009) 748.
[59] F.A. Cardoso, R.G. Pileggi, V.M. John, Bol. Técn. Esc. Politécn. USP **1** (2010) 1.
[60] NBR 12653, "Materiais pozolânicos: requisitos", Ass. Bras. Nor. Técn., Rio Janeiro (2016).
[61] M. Ozturk, O. Akgol, U.K. Sevim, M. Karaaslan, M. Demirci, E. Unal, Constr. Build. Mater. **165** (2018) 58.
[62] H. Chen, Powder Techn. **289** (2016) 1.
[63] H, Motz, J. Geiseler, Waste Manage. **21** (2001) 285.

(Rec. 03/04/2020, Rev. 27/06/2020, Ac. 27/07/2020)