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Use of slag from steelworks (BSSF and BOF) in the manufacture of concrete as a possible environmental solution: case Study with tailings from the CSP of the Port of Pecém in Ceará

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ABSTRACT

The increased demand for raw materials by the construction and processing industries, in particular steel produced from iron ore, has caused negative environmental impacts on the communities located around the steel industries. Therefore, this study validated the hypothesis that it is possible to use the waste produced and disposed of in steel mills (steel mill slag) in the construction industry. In this context, concrete manufacturing experiments were carried out by replacing the aggregate material (sand and cement) with steel mill slag (BSFF and BOF) and technical tests (particle size analysis, magnetic field testing, expansivity and axial strength) to prove the quality of the material produced. The results obtained show that the use of iron ore tailings produced at the Companhia Siderúrgica do Pecém (CSP) in the state of Ceará has potential to produce concrete that can be used in small and large constructions (low-income housing, asphalt sheets, buildings, and viaducts) and that this can help mitigate the negative effects of environmental pollution in the communities surrounding this region, helping to reduce environmental impacts.

Keywords: Environmental impacts, steel mill slag, environmental solutions.

Uso de escórias de aciarias (BSSF e BOF) na fabricação de concreto como possível solução ambiental: Estudo de caso com rejeitos da CSP do Porto do Pecém no Ceará

RESUMO

O aumento da demanda de matéria prima pelas indústrias de construção e transformação, em particular pelo aço produzido a partir do minério de ferro, tem causado impactos ambientais negativos nas comunidades localizadas no entorno das indústrias siderúrgicas. Assim, este estudo validou a hipótese de que é possível usar o rejeito produzido e descartado nas siderúrgicas (escórias de aciarias) na indústria da construção civil. Neste contexto, foram realizados experimentos de fabricação de concreto a partir da substituição do material agregado (areia e cimento) pelas escórias de aciarias (BSFF e BOF) e testes técnicos (análise granulométrica, teste de campo magnético, de expansividade e de resistência axial) para a comprovação da qualidade do material produzido. Os resultados obtidos mostram que o uso dos rejeitos de minérios de ferro produzidos na Companhia Siderúrgica do Pecém (CSP) no Estado do Ceará apresenta potencial para a produção de concreto que podem se usados em pequenas e grandes construções (casas populares, mantas asfálticas, prédios e viadutos) e que isto pode auxiliar as ações mitigadores dos efeitos negativos produzidos pela poluição ambiental observada nas comunidades do entorno desta região, contribuindo para a diminuição dos impactos ambientais.

Palavras-chaves: Impactos ambientais, escórias de aciarias, soluções ambientais.

Introdução

The growing consumption of natural resources generated in the construction industry is associated with population and urban growth, especially in large cities. The waste of materials observed during construction processes, together with the inefficient reuse of waste, has an impact on the environment. Therefore, the development of

efficient processes for reusing waste from these construction processes has been pursued as an industrial advance.

In this context, the waste from the steelmaking process, which is used in various sectors and particularly in the construction industry, is generated during the separation of

molten steel from impurities in steelmaking furnaces and is generally categorized as steelmaking slag, a molten liquid, a complex solution of silicates and oxides, which solidifies with cooling (Polese et al., 2006).

This environmental problem is also faced in the regions around Companhia Siderúrgica do Pecém (CSP), located in the Port of Pecém in the state of Ceará, one of the largest producers of iron ore, which began producing steel slabs in June 2016. CSP's production is aimed at generating high-quality rolled products for the shipbuilding, oil and gas, automotive and construction industries.

There are published studies in the literature that demonstrate the negative environmental impacts faced by the communities living in the area around the CSP plant in the Port of Pecém, impacts arising from the disposal of this industrial waste, slag from steelworks classified as BSSF and BOF (Santos, 2018; Costa and Costa, 2021).

Santos (2018), through visits and interviews with residents of the region, particularly in the community of parada, which is located in the vicinity of the Pecém CSP, showed the emissions of polluting gases and particulate matter, and presents a reflection on the environmental and health impacts of the region's residents, caused by the tailings (steel mill slag) produced at the steel mill. Costa and Costa (2021) use numerical modeling to show the dispersion path of atmospheric pollutants around the Pecém CSP and the impacts on communities and ecosystems in the region.

Thus, these authors agree and mention that the installation of large projects, which require large territorial areas, tend to cause environmental risks, territorial conflicts, atmospheric pollution, demographic and social impacts on the communities located around these projects, in particular the communities around the CSP in the Port of Pecém.

Thus, given the prospect of producing concrete from the tailings (steel mill slag) produced by the CSP steel mill, a steel production industry, partially replacing gravel and sand, providing the same quality, efficiency and performance as concrete produced with traditional materials, the aim is to present a possible alternative to minimize environmental damage in this region.

Use of mining tailings as an environmental alternative

Slag from blast furnaces comes from the reductive fusion of ores to obtain pig iron. It is

formed by combining impurities contained in iron ores with additions of limestone, dolomite and coke and charcoal ash. They are formed during the production of steel in the refining stage where the amount of carbon is controlled, eliminating excess impurities and improving the quality of the steel. This gives rise to steelmaking slags produced in oxygen converter furnaces (LD - Lin-Donwitz and BOF - Blast Oxygen Furnace) and those produced in electric oxygen converter furnaces (EAF - Electric Arc Furnace) (Branco, 2004; Paceco, 2017).

In the granulation stage of the process, the liquid slag produced goes into a granulation drum, where it is treated with water injection for thirty minutes, reducing the free lime that has not reacted, thus creating the BSSF slag (Souza, 2016).

Figures 1 and 2 shows BSSF and BOF slag from steelworks. These are solid granular materials, grey in color, non-flammable and non-radioactive, odorless, insoluble in water, however, in the event of spillage in aquatic environments, alterations may occur with an increase in the pH of the water, thus categorizing it as a potentially polluting product.

Some mining companies have sought to develop new treatments for slag from steelworks, with the aim of rapidly cooling and recycling the slag from the industrial steel production process, in order to minimize waste, eliminate the need to landfill this waste, and reduce the negative environmental impacts around these enterprises (Nascimento, 2023).



Figure 1 - BSFF type.



Figure 2 - BOF type.

Over the years, there have been some attempts in the literature to investigate and validate

the use of this concrete production technique with materials that can be reused, such as BSFF and BOF steel mill slag. Faria (2007) showed in experiments with 50% and 100% replacement of gravel with steel mill slag that it is possible to obtain satisfactory results, compared to the reference mixes of traditional concrete, for use in small civil constructions, obtaining Characteristic Concrete Compressive Strength (FCK) of 56.02 Mpa and 52.84 Mpa, respectively.

In this context, Cardoso (2014) carried out experiments with substitution in proportions of 25%, 50%, 75% and 100%, obtaining the best results for the design with 75% substitution of sand with slag from steelworks produced in the steel industry, and Pacheco (2017) in a more refined experiment, in which he replaced cement with steel slag in proportions of 6%, 10%, 20% and 34%, obtained the best results with the 10% replacement, achieving an FCK of 43.80 Mpa, satisfactory for use in small civil constructions, such as the base of low-cost housing.

Li et al. (2017) tested various industrial rejects (steel mill slag - ASSF, BSSF, BOF and CSSF), with the aim of validating the usefulness of these materials in the production of asphalt mats and concluded that all steel mill slag fillers showed excellent rheological properties (viscosity, thixotropy and yield strength) and can be used as an asphalt material.

Chen et al. (2017) investigated the environmental impact of replacing some of the coarse aggregates used in concrete production with slag produced in a Taiwanese steel mill. They analyzed four replacement proportions (10, 20, 30 and 100%) and concluded that the use of BSSF and BOF slag saves up to 36.41% of the total cost included and reduces the environmental impact by reducing the use of natural aggregate and the disposal of this slag, attesting that this technique can contribute to minimizing the environmental damage caused by the disposal of this industrial waste.

In addition to the use of slag from steelworks as construction materials, some other mining waste has been investigated for this use, with the aim of reducing environmental impacts (Nascimento et al., 2023; Bessa et al., 2022; De Paula et al., 2022; Jaskulski, 2022; Silva, 2022).

Nogueira et al. (2022) mention that the waste produced by steel and mining industries has caused a significant environmental impact on terrestrial and aquatic environments, and that this has a negative impact on the quality of life of the communities around these enterprises. They

therefore investigated and confirmed the feasibility of incorporating waste from the ornamental stone industry into bentonite clay, a material used in waterproofing.

Lemos et al. (2023), highlights the innovative nature of using these materials and the potential for promoting sustainable practices, as well as reducing waste in the construction industry's building processes, reducing environmental degradation and increasing the well-being of communities around mining companies. The study cites the problem with the disposal of the huge amounts of waste generated by the mining industry faced in the state of Goa in India and shows similes problems faced in Brazilian regions.

Material and methods

The experimental part of this study, on the production of High Performance Concrete (HPC) with tailings classified as steel mill slag (BSSF and BOF) from the CSP at the Port of Pecém, was carried out at the IPMATE Laboratory - Institute for Technological Research in Construction Materials (Fortaleza/CE). Experimental tests were carried out in five stages on five samples of material collected, according to the flowchart shown in figure 3: granulometric analysis of the materials collected, magnetic field test, preparation of production traces, expandability tests and axial compression tests.

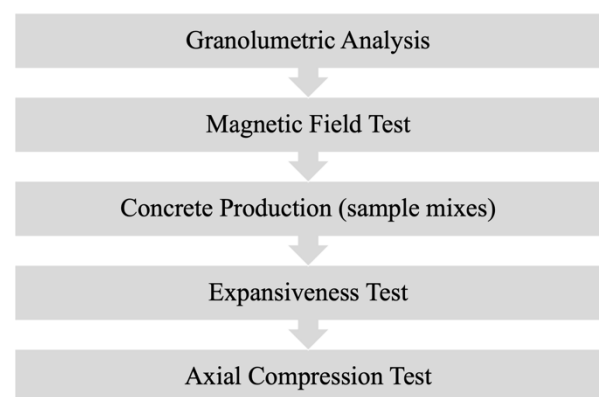


Figure 3 – Design of the experiments.

The particle size tests of the materials collected are of the utmost importance for accurately analyzing the grain size curve indices in each sample, and are indispensable for making the CAD concrete mixes, in which the information obtained from the tests is transformed into technological knowledge that will be discussed as the results of this study (Figure 4).

The magnetic field tests aim to identify the iron particles in the grains of steel mill slag, showing the percentage of iron ores retained in the grains of the samples collected, although the industrial assumption is that the steel mill slag produced is totally demineralized (Figure 5).



Figure 4 – Granulometric analysis.



Figure 5 – Magnet field test.

For the technological control of the concrete produced with the steel slag, tests were carried out in accordance with NBR 12655/2015, with the characteristics of the mix supplied by a company that produces industrial concrete of the CAD (High Performance Concrete) type, using cement and additives and a multifunctional plasticizer retarder with a dosage of 0.8% on the weight of the cement, a superplasticizer with a dosage of 1% on the weight of the cement, and active silica at 10% on the weight of the cement, 8% on the weight of cement, a superplasticizer with a dosage of 1% on the weight of cement, and active silica at 10% on the weight of cement, plus steel mill slag (BSSF and BOF) as a partial substitute for gravel, in the proportions of 20%, 30% and 40%, and BOF slag as a partial substitute for sand at 10% and 20%, according to the data shown in Table 1.

Table 1 – Description of Experiments.

Experiments	Addition Large Aggregates	Addition small aggregates	Replacement of aggregates
Exp. T ₀	0%	0%	Mix – Table 2
Exp. T ₁	20%	0%	Gravel 1/BSSF Gravel 0/BOF
Exp. T ₂	30%	0%	Gravel 1/BSSF Gravel 0/BOF
Exp. T ₃	40%	0%	Gravel 1/BSSF Gravel 0/BOF
Exp. T ₄	30%	10%	Gravel 1/BSSF Gravel 0/BOF Sand/BOF
Exp. T ₅	30%	20%	Gravel 1/BSSF Gravel 0/BOF Sand/ BOF

Table 2 – Description of the reference mixture.

Material	Suppliers	M.C.C. (kg/m ³)	Specific Mass	M/Cement ratio
Cement	CPV APODI	500	3,13	1
Sand	AREIA PT TRANSP	640	2,60	1.28
Gravel 1	NORDBRITA	600	2,64	1.20
Gravel 0	NORDBRITA	400	2,66	0.80
Water	-	190	1,00	0.38
Additive 1	Bauchemie FK 101	4	1,15	0.008
Additive 2	PowerFlow 3100	5	1,20	0.01
Active Silica	Ferbasa	50	2,60	0.10

Eight (8) cylindrical specimens with a diameter of 100 mm and a height of 200 mm were built, in accordance with standard NBR 5739/2018 of the Brazilian Association of Technical Standards (ABNT) for each mix, which were subjected to expansivity and axial strength tests at different concrete curing times (1, 3, 7 and 28 days), as shown in figure 6.



Figure 6 – Concrete production (test specimens).

The expandability tests are important to determine whether during the curing of the concrete (28 days) possible swelling or expandability of the concrete specimens produced with the steel slag (BSSF and BOF) used in the study were observed (Figure 7).



Figure 7 – Expansiveness tests.

The axial compression tests shown here make it possible to assess the reaction of concrete specimens made from the mixes described in Table 1 to compression, i.e., the cylindrical specimens are subjected to the action of an axial force, as shown in figure 8.



Figure 8 – Axial compression tests.

Results and discussion

The results of the technical tests showed that the only parameter measured in the samples of steelmaking slag used in this study (BSSF and BOF) that is outside the norms is the amount of powdery material, i.e., in the BSSF slag samples, on average there is 2.2% powdery material and in the BOF samples a percentage of 7.1%. It should be noted that powdery material is particles smaller than 0.075 millimeters in diameter (NBR 7219). It should be noted that this is not a problem for the

production of CAD-type concrete, as the water absorption of the grains used in the study complies with the technical standards.

Another relevant result found in the experimental tests is the percentage of iron ore in the samples used, an average of 4% in the BSSF slag samples and 9% in the BOF slag samples. This explains the low water absorption, even with the percentage of powdery material found in the samples, as shown in Table 2.

Figure 9 shows the average results of the tests carried out on the CAD concrete samples produced using the mixes mentioned in Table 3.

It can be seen that the first experimental mix (T_1) had similar workability and consistency to the reference mix (T_0). However, it obtained a small reduction in water with an A/C factor of 0.37% (A/C factor is the water/cement ratio, which is inversely proportional to the concrete's axial compressive strength) and an incorporated air content of 1.9%, which is within the 5% defined in technical standard NBR 11768:2011. This sample showed an increase in axial compressive strength compared to the reference mix (T_0) of 6.1% at 3 days and 16.4% at 28 days.

Table 3 – Results of axial compression tests, according to ABNT standards: NBR 5739:2018.

Mix	Date Production	Rupture Date	Breaking Load 1	Breaking Load 2	F ₁	F ₂	Average	Standard Deviation	
T ₀	09/01/2023	10/02/2023	19230	19000	24.50	24.20	24.35	0.21	1 day
T ₁	09/01/2023	10/02/2023	20000	19450	25.48	24.78	25.13	0.50	
T ₂	09/01/2023	10/02/2023	23000	21300	29.30	27.13	28.22	1.53	
T ₃	09/01/2023	10/02/2023	18500	17400	23.57	22.17	22.87	0.99	
T ₄	07/02/2023	08/02/2023	22220	18700	28.31	23.82	26.06	3.17	
T ₅	07/02/2023	08/02/2023	23400	22000	29.81	28.03	28.92	1.26	
T ₀	09/01/2023	12/01/2023	29050	28550	37.01	36.37	36.69	0.45	3 days
T ₁	09/01/2023	12/01/2023	30130	31000	38.38	39.49	38.94	0.78	
T ₂	09/01/2023	12/01/2023	32450	33010	41.34	42.05	41.69	0.50	
T ₃	09/01/2023	12/01/2023	28700	27500	36.56	35.03	35.80	1.08	
T ₄	07/02/2023	10/01/2023	33550	33000	42.74	42.04	42.39	0.50	
T ₅	07/02/2023	10/01/2023	28950	32520	36.88	41.43	39.15	3.22	
T ₀	09/01/2023	16/01/2023	41600	39500	52.99	50.32	51.66	1.89	7 days
T ₁	09/01/2023	16/01/2023	41420	41040	52.76	52.28	52.52	0.34	
T ₂	09/01/2023	16/01/2023	47010	45380	59.89	57.81	58.85	1.47	
T ₃	09/01/2023	16/01/2023	32690	31580	41.64	40.23	40.94	1.00	
T ₄	07/02/2023	14/02/2023	54700	60120	69.68	76.59	73.13	4.88	
T ₅	07/02/2023	14/02/2023	50250	48000	64.01	61.15	62.58	2.03	
T ₀	09/01/2023	06/02/2023	49700	54690	63.31	69.67	66.49	4.49	28 days
T ₁	09/01/2023	06/02/2023	60710	60820	77.34	77.48	77.41	0.10	
T ₂	09/01/2023	06/02/2023	61260	63870	78.04	81.36	79.70	2.35	
T ₃	09/01/2023	06/02/2023	45990	43510	58.59	55.43	57.01	2.23	
T ₄	07/02/2023	07/03/2023	76960	79650	98.04	101.46	99.75	2.42	
T ₅	07/02/2023	07/03/2023	72160	71480	91.92	91.06	91.49	0.61	

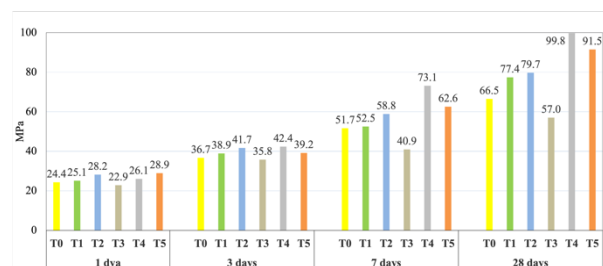


Figure 9 – Average results axial compression tests.

Similar results were found for the second experimental mix (T_2), which had an A/C factor of 0.36% and an incorporated air content of 1.8%, an increase in axial compressive strength of 13.6% in 3 days and 19.8% at 28 days. The fourth experimental mix (T_4) had an A/C factor of 0.35% and an incorporated air content of 1.6%. These variables led to a significant increase in axial compressive strength, with an increase of 15.5% in 3 days and a significant increase of 50.0% in 28 days. The fifth experimental mix (T_5) had an A/C factor of 0.36% and an incorporated air content of 1.7%, an increase in axial compressive strength of 6.72% over 3 days compared to the reference mix and 37.60% over 28 days.

It is worth mentioning that the mixes designed and tested show potential for the manufacture and use of concrete in civil construction, in agreement with the results of published studies (Cardoso, 2014; Pacheco, 2017; Li et al., 2017), with the fourth mix showing greater efficiency, resistance and quality, achieving the highest performance in axial compression with a strength of 101.46 Mpa, which indicates the best replacement ratio of 30% of crushed stone with steel slag and 10% replacement of sand with BOF type slag. The third mix (T_3) showed the lowest performance, as it had the highest water consumption (A/C factor of 0.39%) and incorporated air content (2.30%).

It should be noted that the results obtained are in line with experimental studies that prove the possibility of using industrial waste in the manufacture of concrete for use in small constructions and asphalt material (Cardoso, 2014; Pacheco, 2017; Li et al., 2017). In addition, it should be noted that the concrete produced in this study is of the CAD (High Performance Concrete) type, which is also used in large civil constructions, such as large buildings and urban viaducts. Therefore, it is technically possible to state that the tests carried out in this study, with the CAD concrete produced, show the potential use of iron ore tailings in the construction industry, and can help in projects that aim to contribute to reducing the (negative) environmental impacts associated with the disposal of steel mill slag produced by steel mills.

In addition, the proposed use of iron ore tailings produced in the steel industries installed in the Port of Pecém in the state of Ceará, which according to Santos (2018) and Costa and Costa (2021) has had a negative impact on the quality of life of the communities surrounding these enterprises, agrees with the results of several

studies that attest to the feasibility of incorporating these industrial tailings as an alternative to reduce these impacts on the environment and increase the well-being of the communities surrounding the mining companies (Nascimento et al., 2023; Bessa et al., 2022; De Paula et al., 2022; Jaskulski, 2022; Silva, 2022). And, according to Lemos et al. (2023), it represents an innovation in promoting sustainable practices and reducing waste in construction industry processes.

Conclusions

The first conclusion of this study is the validation of the use of iron ore tailings produced in the steel industry, in particular the use of steel mill slag (BSSF and BOF) produced at the Companhia Siderúrgica do Porto do Pecém (CSP) in the state of Ceará in Brazil, validating the hypothesis considered in the design of the experiments.

It is also concluded that the use of steel mill slag (BSSF and BOF) produced at the Pecém CSP has potential for the production of concrete, including the production of high-performance concrete, which is used in civil construction processes in small and large buildings (low-income housing, asphalt patches, buildings and viaducts).

In addition, considering the environmental problems caused by these industrial tailings in the communities surrounding the CSP region, it is concluded that the use of these industrial tailings produced at the Pecém CSP can help in the planning and implementation of mitigating actions aimed at reducing the environmental pollution observed in the communities surrounding this region, helping to balance an environmental conflict that has arisen.

Finally, as the market price of steel mill slag (BSSF and BOF) is lower than that of traditional aggregates (gravel and sand), it can be concluded that in addition to the possible environmental benefits, the construction industry can also profit from reducing production costs in the region under study.

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