Feasibility Study of Using Steel Slag to Replace Portland Cement in Mortars

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***Abstract*—The construction sector is one of the largest solid waste generators, as well as responsible for extracting a huge volume of natural raw materials. Therefore, it is necessary to reduce the consumption of non-renewable goods by implementing research and new technologies that aim to reduce the impact on the environment. In this context, this research experimentally evaluated the partial replacement of Portland Cement by electric steel slag in mortars, with replacement levels of 25% and 50%, with a water/cement + slag ratio set at 1.5. The tests were performed in a fresh and hardened state, at the ages of 28 and 91 days. The results demonstrate that replacing Portland cement with steel slag influences the properties of mortars, both in the fresh and hardened states. In the fresh state, steel slag provided an increase in workability and a density reduction. In the hardened state, as the residue content increased, there was a decrease in mechanical resistance and an increase in carbonation depth and water absorption. It is therefore concluded that replacing Portland cement with steel slag may be viable, depending on the replacement content, as well as the intended use of the mortar.**

***Keywords*—steel slag, waste, mortar, carbonation**

I. Introduction

The construction sector is responsible for the consumption of several natural resources, in addition to being one of the largest solid waste generators [1].

Another sector that also contributes to the generation of waste is the steel industry, one of the main raw materials used in construction. Around 28% of all waste generated is represented by steel slag, 2% of which is used in cement manufacturing processes.

According to the Brazilian standard NBR 10.004 [2], slag is a non-inert residue, generated during the steel manufacturing process.

Blast furnace slag shows good reactivity at early ages, resulting in adequate resistance in the first 7 days of hydration. In general, mortars and concretes with blast furnace slag have lower permeability and porosity, as well as increasing mechanical resistance over time, due to their denser microstructure [3].

According to Salgado [4], mortars are the most common and traditional coatings used in Brazilian construction, there is practically no project in which they are not used. Fiorito [5] defines mortars as a mixture of binders and aggregates with water, with hardening and adhesion capacity. These materials are composed of sand and binders, which are generally Portland cement and hydrated lime.

Therefore, this paper aims to study the feasibility of using steel slag to replace cement, in mortars, to find a better destination for this waste and minimize possible impacts on the environment.

The incorporation of any residue into cementitious materials requires the evaluation of the physical, mechanical, microstructural, and durability properties of the systems [6].

Therefore, an attempt was made to replace up to 50% of Portland Cement with steel slag, so that the properties and behavior of the mortars in the fresh and hardened states did not change substantially. Mortars were produced with and without replacing Portland cement with steel slag, allowing the comparison of their properties and the evaluation of their behavior over time, as well as the influence of different replacement levels. For this purpose, the following tests were performed: Consistency index; Bulk density; Compressive strength; Tensile strength in flexion; Carbonation; Immersion absorption, and; Capillarity absorption.

II. Materials and Methods

The materials used to produce the mortars were cement, fine aggregate, steel slag, and water.

A. Cement

High initial strength Portland cement (CP V-ARI) was used, classified according to NBR 16697 [7]. This cement has a maximum of 5% added filler in its composition, which makes it one of the purest cement.

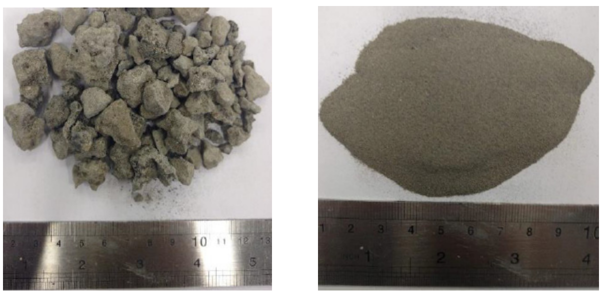
Manuscript received February 1, 2024; revised February 20, 2024; accepted April 5, 2024; published August 27, 2024.

B. Fine Aggregate

The natural fine aggregate used in this research was sand from the Jacuí River, Rio Grande do Sul, classified according to NBR NM 248 [8]. The unit weight was determined according to NBR NM 52 [9], at 1405 kg/m^3. The granulometric composition of the fine aggregate was carried out according to NBR NM 248 [8] and NBR 7211 [10]. The test was performed with previously dried samples, using a vibrating sieve, with a frequency of 15Hz, a set of normal series sieves, and a 0.1 g precision balance.

C. Steel Slag

The used steel slag was collected from a steel plant located in the metropolitan region of the city of Porto Alegre, state of Rio Grande do Sul, in Brazil. The slag was stored at the steel plant for approximately six months, aiming for stabilization. The material was subjected to grinding in a ball mill, with 1000 ml capacity bottles. The procedure was standardized, so that the material was subjected to grinding for forty minutes and subsequently sieved through a 200 mesh (0.075 mm), to guarantee the finest and most homogeneous grains possible. Fig. 1 shows the slag appearance before and after the grinding process.



(a) (b)

Fig. 1. (a) Granulated slag (b) Milled slag.

The methods determined the material unit weight indicated in NBR NM 45 [11], resulting in 1281 kg/m^3. The waste average rate of water absorption was 0.65%.

The mortar proportion was set at 1:4.5 (cement: sand, in volume, dry materials), to compare the influence of slag on poor mortar and compare the results obtained with these and other authors. The first dosage was performed without the presence of residue, which was considered a reference, that is, with a 0% residue content, called A0. Two levels of substitution of Portland cement for slag were also adopted, 25% and 50%, called A25 and A50, respectively. The mixing water was established based on the water/cement + slag ratio, set at 1.5. The mortar preparation was carried out following NBR 13276 [12].

The tests to evaluate the mortar's behavior with and without steel slag were divided into fresh state tests and hardened state tests.

1) Fresh state tests

The mortars were analyzed in the fresh state using consistency index and specific gravity tests. After producing the mortars, the consistency index was determined, as indicated by NBR 13276 [12]. The spread was measured in three diameters and the average was taken for each content. The specific gravity was determined following NBR 13278 [13], through the relationship between the mass of the container containing mortar, the mass of the empty container and the container volume.

2) Hardened state tests

In the hardened state, the following tests were carried out: Compressive strength; Tensile strength in flexion; Immersion absorption; Capillarity absorption, and Carbonation.

After preparing the mortars, 18 test specimens measuring 4 cm × 4 cm × 16 cm were molded for each slag content, by NBR 13279 [14]. The specific gravity was carried out at 28 days, as recommended by NBR 13280 [15].

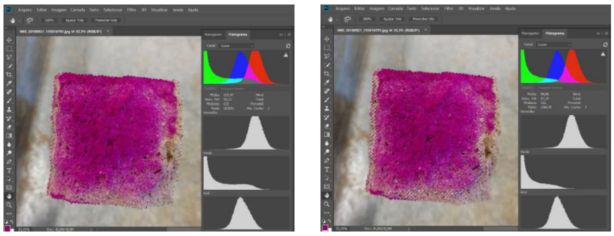
The specimen's tensile and compressive strengths were obtained for the ages of 28 and 91 days, following the prescription of NBR 13279 [14]. The specimens were also analyzed for absorption by immersion, as adapted from NBR 9778 [16]. Capillary absorption analysis was performed as indicated in NBR 15259 [17], after 28 days of curing.

To determine the carbonation of mortars with steel slag, the test specimens were subjected to accelerated aging cycles, where they underwent periods of immersion in water and oven drying for 90 days. Thus, the specimens were repeatedly subjected to immersion in water for 24 hours, exposure to air for 48 hours, and drying for 24 hours.

After this process, the specimens were ruptured and a solution of 1% phenolphthalein, 70% ethyl alcohol, and 29% water was sprayed inside. In the area where the specimens had a pink color, no carbonation occurred. Therefore, where the solution was colorless, the carbonated depth was measured as shown in Fig. 2. Data were collected at the ages of 28 and 91 days after molding the specimens.

Fig. 2. Carbonation test.

The carbonated area was measured in two ways. Firstly, a caliper was used to measure the carbonate thickness presented by the specimens. The second measurement was performed using the Adobe Photoshop CC 2018 software as shown in Figs. 3 and 4. From an image of the specimens, the total number of constituent pixels was measured as shown in Fig. 3a. Then, using the "Color range" command as shown in Fig. 4, the area that showed pink color was selected, and the number of pixels in this area was measured again as shown in Fig. 3b.



(a) (b)

Fig. 3. Image processing with Adobe Photoshop CC 2018. (a) Total pixels; (b) Pink pixels.

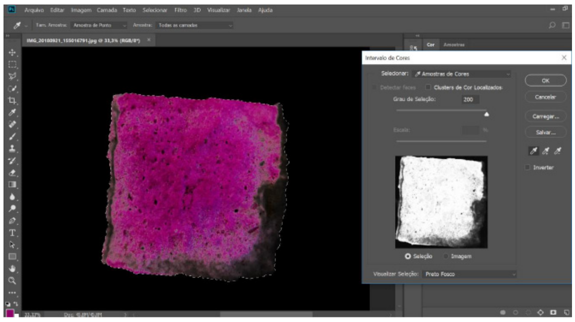


Fig. 4. Image processing with Adobe Photoshop CC 2018. Color range command.

III. Results and Discussion

A. *Fresh State Results*

To analyze the properties of mortars in the fresh state, consistency index and mass density tests were carried out, the results of which are presented in Table I.

TABLE I. Average Results of the Consistency Index and Mass Density in the Fresh State

Mortar	Consistency Index (mm)	Standard Deviation (mm)	Coefficient of Variation (%)
A0	200.00	0.35	0.18
A25	203.00	0.35	0.17
A50	204.00	0.07	0.03
Mortar	**Mass Density (Kg/m^3)**	**Standard Deviation (Kg/m^3)**	**Coefficient of Variation (%)**
A0	1752.00	4.43	0.25
A25	1741.00	1.11	0.06
A50	1723.00	1.75	0.10

There are differences in the values found, both for the consistency index and the mass density of the mortars under study. Furthermore, it is observed that the consistency index values are inversely proportional to the mass density values.

For the consistency index, an increase in spreading was identified with the addition of residue. In other words, the residue positively influences the workability of the studied mortars. This fact can be explained by the pre-fixation of the water/cement + slag ratio, thus showing that slag exerts a significant influence on mortars in the fresh state, providing an increase in workability, possibly due to the slag's rounded shape.

For the mass density test, when comparing the reference proportion with the others (25% and 50% substitution), it was found that the highest value was for the mortar without replacing Portland cement with steel slag. This is an indication that, possibly, there was an increase in the void ratio of mortars with slag. These voids could be related to the density of the materials used.

Therefore, it is concluded that the replacement of Portland Cement by steel slag influences the results found for mass density and consistency index of mortars in the fresh state.

B. *Hardened State Results*

1) *Specific gravity*

Table II presents the average values of specific gravity at 28 days.

TABLE II. Average Specific Gravity

Mortar	Specific Gravity (Kg/cm^3)	Standard Deviation (Kg/cm^3)	Coefficient of Variation (%)
A0	1670.70	4.35	0.26
A25	1642.32	12.58	0.77
A50	1637.63	82.09	5.01

Regarding the specific gravity, it was observed that there is no significant difference between the reference mortar and the replacement levels analyzed. Despite the small difference, the results found are in accordance with the tests carried out for specific gravity in the fresh state and water absorption. It was possible to identify an increase in the porosity of the analyzed mortars, thus influencing the results found in this test.

2) *Flexural tensile strength and compressive strength*

The average values found for each mortar in the flexural tensile and compression strength tests, at 28 and 91 days, are shown in Tables III and IV, respectively.

TABLE III. Average Flexure Tensile Strength and Compression at 28 Days

Mortar	Average Tensile Strength at 28 days (MPa)	Standard Deviation (MPa)	Coefficient of Variation (%)
A0	1.40	0.20	12.10
A25	0.90	0.00	2.70
A50	0.60	0.00	4.87
Mortar	**Average Compressive Strength at 28 days (MPa)**	**Standard Deviation (MPa)**	**Coefficient of Variation (%)**
A0	4.50	0.30	6.91
A25	2.20	0.10	5.79
A50	1.10	0.10	13.08

TABLE IV. Average Flexure Tensile Strength and Compression at 91 Days

Mortar	Average Tensile Strength at 91 days (MPa)	Standard Deviation (MPa)	Coefficient of Variation (%)
A0	2.10	0.00	1.32
A25	1.00	0.00	4.93
A50	0.80	0.00	0.82
Mortar	**Average Compressive Strength at 91 days (MPa)**	**Standard Deviation (MPa)**	**Coefficient of Variation (%)**
A0	3.60	0.40	11.68
A25	1.90	0.10	6.66
A50	1.40	0.20	15.22

There is a reduction in mechanical resistance in the mortars studied with the increase in residue content, both for flexural tensile strength and compressive strength at 28 and 91 days. This behavior may be related to the higher void content, evidenced by the lower densities for mortars with steel slag and the replacement of Portland Cement by the residue.

3) *Water absorption*

Analyzes of the properties of mortars with the replacement of Portland Cement by steel slag in terms of water absorption, immersion absorption, and capillary absorption tests were carried out. The average results obtained are found in Tables V and VI.

TABLE V. AVERAGE WATER ABSORPTION RESULTS BY IMMERSION

Mortar	Average Immersion Absorption (%)	Standard Deviation (%)	Coefficient of Variation (%)
A0	14.40	0.20	1.47
A25	15.50	0.10	0.79
A50	15.90	1.60	9.90

The water absorption values due to mortar immersion were very close. This result is possibly due to the time interval in which the measurements were carried out, according to the proposed methodology, where total saturation of the specimens occurred in the period corresponding to the first collection of results due to the porosity of the mortars.

TABLE VI. AVERAGE CAPILLARITY WATER ABSORPTION RESULTS

Mortar	Average Capillarity Absorption (g/cm³)	Standard Deviation (g/cm³)	Coefficient of Variation (%)
A0	1.00	0.20	22.76
A25	1.60	0.10	3.71
A50	1.40	0.00	0.33
Mortar	**Average Capillarity Coefficient ($g/dm^2.min^{1/2}$)**	**Standard Deviation ($g/dm^2.min^{1/2}$)**	**Coefficient of Variation (%)**
A0	16.70	2.40	14.10
A25	21.90	1.00	4.60
A50	16.50	0.30	1.50

Regarding the capillarity water absorption tests and capillarity coefficient, there is a difference between the mortars, demonstrating that the slag is influencing the water absorption by capillarity in the mortars. Probably due to the increase in mortar porosity with the replacement of Portland Cement with steel slag. The results show that the lower the density, the greater the porosity and water absorption.

4) *Carbonation*

Table VII presents the carbonation depth average values of the analyzed mortars, at 28 and 91 days, based on measurements performed with a caliper.

The 50% replacement resulted in greater carbonation depths, both at 28 days and 91 days. The values for A50 at 91 days were more than three times higher than the values for the A0 reference mortar.

TABLE VII. AVERAGE CARBONATION DEPTH

Mortar	Average Depth at 28 Days (mm)	Standard Deviation (mm)	Coefficient of Variation (%)
A0	2.84	1.25	44.05
A25	2.47	0.37	15.02
A50	5.86	3.13	53.39
Mortar	**Average Depth at 91 Days (mm)**	**Standard Deviation (mm)**	**Coefficient of Variation (%)**
A0	11.62	0.65	5.58
A25	15.61	0.87	5.59
A50	40.00	0.00	0.00

To better assess the influence of slag content on carbonation, Table VIII presents the values found for the percentage of carbonated area measured with the Adobe Photoshop CC 2018 software.

TABLE VIII. CARBONATED AREA USING ADOBE PHOTOSHOP CC 2018

Mortar	Average Carbonated Area at 28 Days (%)	Standard Deviation (%)	Coefficient of Variation (%)
A0	5.50	1.10	1.37
A25	11.50	2.00	17.05
A50	29.00	8.30	2.52
Mortar	**Average Carbonated Area at 91 Days (%)**	**Standard Deviation (%)**	**Coefficient of Variation (%)**
A0	85.70	0.30	0.33
A25	98.60	1.60	1.58
A50	99.80	0.20	0.19

At 28 days, the 50% content has an average carbonated thickness and a carbonated area larger than the others. As this content presents lower cement consumption and a high water/binder ratio, the penetration of carbon dioxide possibly occurs more easily, resulting in greater carbonation of the specimens.

At 91 days, there was a minor difference between the 25% and 50% replacement levels, concerning the reference sample, since the first one presents practically complete carbonation. Thus, increasing the replacement content of Portland Cement with steel slag provides an increase in carbonation.

This advancement in the carbonation process must be taken into account when replacing Portland Cement with steel slag in mortars and concretes, as it directly influences the durability of the mixtures.

IV. CONCLUSIONS

Based on the production of reference mortars (without residue) and with replacement levels of 25% and 50%, it was possible to assess the feasibility of using steel slag to replace Portland Cement in mortars.

The main conclusions obtained from the analysis of this research results are:

- The results obtained for samples of Portland Cement replacement with steel slag showed low variability;
- Steel slag influenced the workability of the analyzed mortars, and the higher the replacement content, the greater the workability;

- The use of steel slag to replace Portland Cement increases the mortar's porosity;
- Replacing Portland Cement with steel slag resulted in increased water absorption by capillarity;
- The increase in the replacement content of Portland Cement with steel slag favors the increase in the carbonation depth and the decrease in the mechanical resistance of the mortars analyzed;
- At 28 and 91 days, mortars with replacement levels of 25% and 50% showed tensile and compressive strengths lower than the reference mortar.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Vítor L. da Silva and Carina M. Stolz conducted the research; Carina M. Stolz, Bruno B. F. da Costa, Mayara Amario, and Assed N. Haddad analyzed the data and wrote the paper; all authors had approved the final version.

Acknowledgment

Assed Haddad would like to acknowledge Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), and Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ).

References

[1] V. Agopyan and V. M. John, *The Sustainability Challenge in Construction*, São Paulo: Blucher, vol. 5, p. 141, 2011.
[2] *Solid Waste–Classification*, Associação Brasileira De Normas Técnicas *NBR 10004*, 2004.
[3] A. Neville, "The confused world of sulfate attack on concrete," *Cement and Concrete Research*, vol. 34, no. 8, pp. 1275–1296, 2004.
[4] J. C. P. Salgado, *Techniques and Practices for Construction*, 2nd ed., São Paulo: Érica, 2009.
[5] A. J. S. I. Fiorito, *Mortar and Coatings Manual: Studies and Execution Procedures*, São Paulo, SP: Pini, 2009.
[6] J. L. Calmon, *Construction Materials and Principles of Materials Science and Engineering*, São Paulo: IBRACON, 2007.
[7] Portland cement–Requirements, Associação Brasileira De Normas Técnicas NBR 16697, 2018.
[8] Aggregates–Determination of Granulometric Composition, Associação Brasileira De Normas Técnicas NBR NM 248, 2001.
[9] Fine aggregate–Determination of specific mass and apparent specific mass, Associação Brasileira De Normas Técnicas NBR NM 52, 2009.
[10] Aggregates for Concrete-Requirements, Associação Brasileira De Normas Técnicas NBR 7211, 2022.
[11] Aggregates–Determination of unit mass and void volume, Associação Brasileira De Normas Técnicas NBR NM 45-2006.
[12] Mortars applied on walls and ceilings–Determination of the consistency index, Associação Brasileira De Normas Técnicas NBR 13276, 2016.
[13] Mortars applied on walls and ceilings–Determination of the specific gravity and the air-entrained content in the fresh stage, Associação Brasileira De Normas Técnicas NBR 13278, 2005.
[14] Mortars applied on walls and ceilings–Determination of the flexural and the compressive strength in the hardened stage, Associação Brasileira De Normas Técnicas NBR 13279, 2005.
[15] Mortars applied on walls and ceilings–Determination of the specific gravity in the hardened stage, Associação Brasileira De Normas Técnicas NBR 13280, 2005.
[16] Hardened mortar and concrete–Determination of absorption, voids, and specific gravity, Associação Brasileira De Normas Técnicas NBR 9778, 2005.
[17] Mortars applied on walls and ceilings–Determination of water absorption coefficient due to capillary action, Associação Brasileira De Normas Técnicas NBR 15259, 2005.