Reinsertion of basic granulated blast furnace slag as replacement matter in mortars

CARMEN Couto Ribeiro¹,a*, LUCIANA Dias Martins da Costa².b, TADEU Starling³,c, PAULA Bamberg⁴.d and JOANA Darc Silva Pinto⁵.e


¹carmencoutu@oi.com.br, ᵇludiasmc@gmail.com, ᶜtaudeustarlingbh@oi.com.br, ᵈpaula.bamberg@hotmail.com, ᵉjoanadarc@pucminas.br

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Abstract: Slag is a type of waste material produced during the smelting or refining of iron ore, which, after coming out of the blast furnace, undergoes a slow cooling process that crystallizes it, or a sudden cooling process that leads to its vitrification, thus producing a granulated slag. This waste material is produced in large scale in the state of Minas Gerais. This study deals with the insertion of basic granulated slag to replace natural aggregate in mortars, comparing a reference mortar made with natural aggregate against mortars in which that aggregate is partially or totally replaced with slag. Grain sizing, consistency, compressive strength and water absorption indices were tested. In accordance with standard NBR 7211, the natural aggregate utilized is situated in excellent position, the aggregate with partial replacement in a usable position and the aggregate with total replacement goes over this limit. Consistency indices, considering a 0.50 water / binder ratio, were 220mm for the reference mortar and the one with partial replacement. The mortar with total replacement disintegrated. Compression strengths were 32 MPa both for the reference mortar and the one with partial replacement and of 20MPa for the mortar with total replacement. Water absorption was less than 11% for all assessed mortars. The analysis of the results shows that mortars produced with total replacement are not indicated for use and that mortars with partial replacement of natural aggregate (sand) with basic granulated slag comply with strength, durability and sustainability standards and can be employed in construction engineering.
Introduction

Blast furnace slag is a steel industry waste obtained during iron ore mineral reduction processing, and its chemical composition is determined in function of the elements that contribute to its production: gangue (ore inert material), fluxes (substances or materials that aid in metal smelting) and ashes from utilized fuels (charcoal or coke). Slags are mainly composed of silica (SiO$_2$) and alumina (Al$_2$O$_3$) from gangue, and of lime (CaO) from limestone used as flux.

From a siderurgical point of view, one of the slag’s main properties is its fluidity, which depends on the lime and silica ratio, denominated simplified basicity index. The lime content has special importance for removing sulfur. In a charcoal-burning blast furnace this feature is secondary since this type of fuel contains barely any sulfur. The high sulfur content present in coke requires a larger amount of lime, thus producing basic slag. Blast furnace slags feature predominantly silica as their main component and are classified as acidic [1].

The molten slag coming from the blast furnace may undergo different cooling processes, which will give the material particular characteristics. A sudden cooling shall lead to its vitrification, thus creating a granulated slag that is produced on a large scale in the State of Minas Gerais. It is partially utilized by the cement industry and can also be used as a fine aggregate [2].

According to Mussucato [3], acid slags are also classified as artificial pozzolanas. This definition is of utmost importance to determine the maximum content to be added to the concrete within the limits established by the cement production norm. Mineral additions made to cement, such as pozzolanas, which partially replace clinker, contribute to reducing the environmental impact of civil engineering construction and of other sectors as the volume extracted of raw material is reduced and large amounts of waste matter that were to be disposed of are used.

Pozzolanas are natural or artificial materials that contain pozzolanically active silica, with little or no cementitious properties. When pozzolanas are pulverized and in contact with humidity, they react with calcium hydroxide, forming products with cementitious properties. The silica present in pozzolana reacts with calcium hydroxide Ca(OH)$_2$ that is released when cement is hydrated, thus forming calcium silicates.

Mineral additions used in mortars while producing the mortar or inserted previously in the cement lead to the improvement of technical features of the final product, as they modify the internal structure of the hydrated cement paste. The use of additions leads to impacts such as the reduction of porosity, and in some cases, to gains in strength. This also leads to a decreased hydration heat and, consequently, reduces thermally originated fissures.

In order to obtain a quality mortar it is necessary that all inert material grains be incorporated into the paste and that the voids between them be totally filled. A quality mortar must comply with requirements of mechanical strength, workability, impermeability, adherence and durability.

Ready-made mortar mixes have been used to replace traditional mortars in civil engineering construction. The ready-made mix is a mix of binders, aggregates and additives which has the advantage of requiring only the addition of water to be used at the construction site [4].

According to Rossa and Portella [5] improvements in workability have been noted as a result of the increased volume of blast furnace slag additions, ranging from 5 to 20%, made to ACI type ready-mix mortars.

The use of waste matter in civil engineering construction products is currently featured as a viable alternative of noteworthy importance. In view of the capacity of cementitious matrixes to stabilize contaminating matter present in some types of waste, more studies in this field of knowledge must be encouraged [6].
Experimental Research

The insertion of basic granulated slag to replace natural aggregate in mortars was assessed by comparing a reference natural-aggregate mortar with mortars featuring 35%, 50% and 100% replacement with slag, respectively. Tests were made to verify chemical composition, grain sizing, consistency, compression strength and water absorption indexes.

The granulometric composition of aggregates was studied to compare how the replacement of natural aggregate with slag influenced workability, compacticity and resistance to mechanical stresses applied to mortars [7, 8].

The consistency of mortars was assessed in the workability study by comparing the consistency indexes in a truncated cone as established by NBR 13276 [9].

Strength was assessed with the compression strength test as established by NBR 7215. Cylindrical bodies of proof were molded in 5x10cm, which, except for those bodies of proof tested on the 7th day, remained in the moist chamber for 28 days [10].

Water absorption in mortars was tested with 5x10cm bodies of proof, which were kept in an autoclave at 105± 5°C during variable time periods. Once dried out, the bodies of proof were immersed in water at 23±2°C for time periods ranging from 24 to 72 hours. The absorption was measured by mass gains. From the data collected during these tests, the specific mass and the concrete void indexes were defined [11].

Results and Discussion

The constituent materials used in the mortars under study were Portland Cement CPII E-32, natural sand and basic granulated blast furnace slag.

The chemical composition of Portland Cement CPII E-32 and of the basic granulated slag are presented in Table 1.

<table>
<thead>
<tr>
<th>Chemical Composites</th>
<th>Portland Cement CPII E 32 [%]</th>
<th>Blast Furnace Slag [%]</th>
<th>Normative Limits [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>58.9 – 66.8</td>
<td>41.70</td>
<td>38 to 48</td>
</tr>
<tr>
<td>SiO₂</td>
<td>19.0 – 24.2</td>
<td>33.47</td>
<td>29 to 38</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.9 – 7.3</td>
<td>14.12</td>
<td>13 to 24</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.8 – 5.0</td>
<td>1.07</td>
<td>4</td>
</tr>
<tr>
<td>MgO</td>
<td>0.8 – 6.0</td>
<td>5.90</td>
<td>2</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.9 – 3.0</td>
<td>0.82</td>
<td>2</td>
</tr>
<tr>
<td>Basicity Index – V*</td>
<td>3.1 – 2.7</td>
<td>1.25</td>
<td>-</td>
</tr>
<tr>
<td>Siderurgical Classification</td>
<td>-</td>
<td>Basic</td>
<td>-</td>
</tr>
</tbody>
</table>

*Source: [1]

\[
V = \frac{%CaO}{%SiO_2}
\]

In Table 1, it can be noted that Portland cement and blast furnace slag have the same chemical composites in different amounts.

The slag under study is classified as basic from a siderurgical point of view, since the lime content in this slag is greater than the silica content.
Grain sizing
The use of basic granulated blast furnace slag provided for the verification of the material’s influence as a fine aggregate over the quality of the mortar. Three types of replacements were made: 35%, 50% and 100%.

The sand featured a grain measure module of 2.8mm and a maximum grain size of 4.8mm. It should be noted that the sand was within the optimum range established by norm ABNT 7211, which states the grain measure module should range from 2.20mm to 2.90mm (Fig. 1).

For the 65% sand ratio and 35% slag ratio, the fine aggregates presented a grain size module of 2.85 and a maximum grain size of 4.8mm, thus being within the usable range (Fig. 2).
For the 50/50 sand/slag ratio, the fine aggregates presented a grain size module of 2.96 and a maximum grain size of 4.8mm (Fig. 3).

![Figure 3 – Grain sizing curve 50% sand and 50% slag](image)

When replacing sand with 100% slag, the aggregate presented a grain size module of 3.63 and a maximum grain size of 4.8mm. It should be noted that the grain size module of the slag exceeds the usable range as established by the norm (Fig. 4).

![Figure 4 – Grain sizing curve of slag](image)
Consistency Indexes

The consistency indexes obtained from the mortars with different blast furnace slag content are shown in Table 2.

Table 2 – Consistency Index

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Dosage ratio (cement:sand:slag)</th>
<th>Water/binder Ratio</th>
<th>Replacement w/ Slag [%]</th>
<th>Consistency Index [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>1 : 3</td>
<td>0.50</td>
<td>0</td>
<td>223</td>
</tr>
<tr>
<td>Slag 35</td>
<td>1 : 1.95 : 1.05</td>
<td>0.50</td>
<td>35</td>
<td>217</td>
</tr>
<tr>
<td>Slag 50</td>
<td>1 : 1.5 : 1.5</td>
<td>0.50</td>
<td>50</td>
<td>217</td>
</tr>
<tr>
<td>Slag 100</td>
<td>1 : 3</td>
<td>0.50</td>
<td>100</td>
<td>Disintegrated</td>
</tr>
</tbody>
</table>

The figure obtained of 225 ± 5 mm both for the reference mortar and the mortars with slag replacement of 35% and 50%, respectively, meets the consistency index established in NBR 5752. The mortars with 100% slag replacement disintegrated.

Compression Strength

The compression strength of mortars is associated to paste’s reaction to hydration. The compression strength at the 28th day was adopted as an assessment parameter to compare the reference mortar and the mortars in which blast furnace slag replaced the traditional fine aggregate.

The axial compressive strength test results of the mortars are presented in Table 3 and Fig. 5.

Table 3 – Compressive strength

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Dosage ratio (cement:sand:slag)</th>
<th>Water/binder ratio</th>
<th>Replacement w/Slag [%]</th>
<th>Shear stress 7 days [MPa]</th>
<th>Shear stress 28 days [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>1 : 3</td>
<td>0.50</td>
<td>0</td>
<td>23.0</td>
<td>32.5</td>
</tr>
<tr>
<td>Slag 35</td>
<td>1 : 1.95 : 1.05</td>
<td>0.50</td>
<td>35</td>
<td>31.3</td>
<td>40.2</td>
</tr>
<tr>
<td>Slag 50</td>
<td>1 : 1.5 : 1.5</td>
<td>0.50</td>
<td>50</td>
<td>29.1</td>
<td>32.8</td>
</tr>
<tr>
<td>Slag 100</td>
<td>1 : 3</td>
<td>0.50</td>
<td>100</td>
<td>16.2</td>
<td>21.1</td>
</tr>
</tbody>
</table>

Figure 5 – Comparing compression strength x shear stress age
The analysis of Table 3 and of Fig. 5 shows that the 35% and 50% replacements produced a gain in strength in relation to the reference dosage. It should also be noted that the full replacement produces compression strength below the values found in the reference mortar.

**Water absorption**

Table 4 shows the results obtained in the mortar water absorption tests.

<table>
<thead>
<tr>
<th>Mortar</th>
<th>Dosage Ratio (cement:sand:slag)</th>
<th>Water/binder Ratio</th>
<th>Replacement w/ slag [%]</th>
<th>Absorption during immersion [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>1 : 3</td>
<td>0.50</td>
<td>0</td>
<td>10.8</td>
</tr>
<tr>
<td>Slag 35</td>
<td>1 : 1.95 : 1.5</td>
<td>0.50</td>
<td>35</td>
<td>8.5</td>
</tr>
<tr>
<td>Slag 50</td>
<td>1 : 1.5 : 1.5</td>
<td>0.50</td>
<td>50</td>
<td>8.6</td>
</tr>
<tr>
<td>Slag 100</td>
<td>1 : 3</td>
<td>0.50</td>
<td>100</td>
<td>11.8</td>
</tr>
</tbody>
</table>

With regard to the absorption tests, the results obtained with mortars containing blast furnace slag proved to be very close to the results of the reference mortar.

**Final Considerations**

The results obtained showed that mortars produced with 35% and 50% slag replacement did not feature any changes regarding consistency, compression strength and water absorption during immersion, which confirms the possibility of slag to be used as a partial replacement material for natural fine aggregate in mortars.

From a sustainability point of view, the importance of this study is based on the need to compare the performance of replacement materials against traditional materials with the purpose of promoting the insertion and recycling of industrial wastes in civil engineering construction processes.

**References**


