Original Article

Comparison of Kambara reactor slag with blast furnace slag for Portland cement industry applications

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\textbf{Abstract}

This work was aimed at comparing the physical and chemical properties of the Kambara Reactor Slag (KRS) and a Granulated Blast Furnace Slag (GBFS) for achieving partial substitution of GBFS for the KRS. The KRS and GBFS were characterized by chemical, mineralogical, thermal, granulometric, visual, and microscopic analyses, which included the determination of the unit weight, pH, and ability to ground. The KRS had lower concentrations of SiO\textsubscript{2}, Al\textsubscript{2}O\textsubscript{3}, and MgO and higher percentages of total Fe and Fe\textsuperscript{2+} than the GBFS. Moreover, compared to the GBFS, it was crystalline (the GBFS was amorphous); had a larger specific area with a final fraction of 150 \mu m, higher unit weight, and predominantly spherical particles; and was more alkaline. Thus, the KRS is a by-product that may be useful for Portland cement manufacturing; however, the thermal, mechanical, or chemical activations will be needed to attain the cement requirements.

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1. Introduction

Steel is one of the most widely used materials worldwide owing to its characteristics and properties. The steel industry generates large amounts of waste at each stage of steel production, including reduction and refining. During reduction, when a blast furnace is used, the by-product is pig iron. Refining includes the desulfurization of steel and consists of the reduction of the sulfur present in the metal by the formation of stable sulfides. These sulfides are removed from the liquid pig iron by skimming or scraping the slag formed on the surface, preventing the reaction product from being reversed and new solubilization of the sulfur to occur in the bath. In both stages, large quantities of by-products are formed, resulting in an environmental problem for the steel industry.

One alternative use of blast furnace slags has been in the manufacture of Portland cement. Compared to fly ash, silica fume, and pozzolanas, cementitious materials must have relatively constant chemical compositions, low heat of hydration, high sulfate and acid resistance, better workability, and higher...
The ultimate to Portland steelmaking 2.1. kg the manufacture chemical GBFS, made distance land mortar.

Table

20.0% Clinker Table

KRS – low-dimensional already cement. This work aimed at the comparison of the physical and chemical properties of the Kambara Reactor Slag (KRS) and a GBFS to achieve partial substitution of the blast furnace slag for the KRS.

2. Materials and methods

2.1. GBFS and KRS

The KRS, as shown in Fig. 1, was provided by Arcelor Mittal Tubarão, located in Serra, Espírito Santo, Brazil. One-hundred kg of the material with granulometry between 0 and 5 mm was made available for performing the proposed tests.

2.2. Portland cement type III

Portland cement type III (CP III) was used as a base to which the KRS was added; CP III was selected because this type of cement is already a constituent of clinker, gypsum, granulated slag, and carbonate materials. Table 1 lists the mass percentages of each cement raw material determined from the data provided by the manufacturer.

2.3. Chemical analysis

Chemical analyses of the slags were performed at the Arcelor-Mittal Tubarão Chemical Laboratory using the techniques and equipment listed in Table 2.

In addition to the tests cited in Table 2, the percentage of loss to fire by gravimetry, a technique that allows determining a substance via mass change, was also recorded.

2.4. Mineralogical analysis

X-Ray diffraction (XRD) was performed to verify the crystalline state of the GBFS by-products and KRS in addition to identifying the phases present in each sample. The tests were conducted with a Bruker D8 phase diffractometer, from the Materials Characterization Laboratory of the IFES campus Vitória. The settings used for all the tests were 40 kV and 10 mA, with 0.02° step, and an observation range of 10° ≤ 2θ ≤ 100°.

Table 1 – Percent composition of CP III cement used.

<table>
<thead>
<tr>
<th>Clinker</th>
<th>GBFS</th>
<th>Plaster</th>
<th>Filler</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0%</td>
<td>66.5%</td>
<td>1.9%</td>
<td>1.6%</td>
</tr>
</tbody>
</table>

Table 2 – Techniques used in chemical analyses.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Analytical method</th>
<th>Equipment/model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al₂O₃</td>
<td>X-ray fluorescence (XRF)</td>
<td>THERMO ARL9900</td>
</tr>
<tr>
<td>CaO</td>
<td>XRF</td>
<td>THERMO ARL9900</td>
</tr>
<tr>
<td>MgO</td>
<td>XRF</td>
<td>THERMO ARL9900</td>
</tr>
<tr>
<td>MnO</td>
<td>XRF</td>
<td>THERMO ARL9900</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>XRF</td>
<td>THERMO ARL9900</td>
</tr>
<tr>
<td>SiO₂</td>
<td>XRF</td>
<td>THERMO ARL9900</td>
</tr>
<tr>
<td>C total</td>
<td>Combustion</td>
<td>LECO CS444</td>
</tr>
<tr>
<td>S total</td>
<td>Combustion</td>
<td>LECO CS444</td>
</tr>
<tr>
<td>Fe</td>
<td>Volumetry</td>
<td>–</td>
</tr>
<tr>
<td>FeO</td>
<td>Volumetry</td>
<td>–</td>
</tr>
<tr>
<td>Fe total</td>
<td>Volumetry</td>
<td>–</td>
</tr>
<tr>
<td>MgO</td>
<td>ICP OES</td>
<td>THERMO iCAP 7000</td>
</tr>
<tr>
<td>ZnO</td>
<td>ICP OES</td>
<td>THERMO iCAP 7000</td>
</tr>
<tr>
<td>Na₂O</td>
<td>ICP OES</td>
<td>THERMO iCAP 7000</td>
</tr>
<tr>
<td>K₂O</td>
<td>ICP OES</td>
<td>THERMO iCAP 7000</td>
</tr>
</tbody>
</table>

Fig. 1 – Slags: (a) GBFS and (b) KRS.
2.5. **Thermogravimetry (TG) and differential scanning calorimetry (DSC)**

Thermogravimetry (TG) measures the mass variation of a sample resulting from physical or chemical transformations when subjected to a controlled temperature gradient. In comparison, differential scanning calorimetry (DSC) measures the energy difference between a sample and thermally inert reference material required to keep both at the same temperature. The tests were performed at the Materials Characterization Laboratory of the IFES campus Vitória using a Netzch model STA 449 F3 Jupiter. The samples were subjected to a temperature ramp to 1000 °C, with a heating rate of 10 °C/min in air.

2.6. **Granulometric analysis**

To determine the particle size distribution of the KRS and GBFS slags, the samples were quarantined with a Jones divider. The granulometric distribution of each slag was determined according to the ABNT NBR NM 248:2003 standard [22], using a PRODUTEST sieve agitator with a 6.3 mm intermediate-series sieve and set of normal-series sieves of 4.8 mm to 0.15 mm, with a cover and bottom for each.

Both the quarrying and granulometry tests were performed at the Concrete Laboratory of the Federal Institute of Espírito Santo Vitória Campus. In addition, the volumetric distribution of the GBFS and KRS particles at 150-μm-throughput was determined using the Mastersizer Hydro 2000 Hydro MU from Malvern, housed at the Laboratory of Ceramics on the IFES campus Vitória.

2.7. **Determination of the unit weight**

The KRS unit weight was determined by Kaeme Engenharia, according to ABNT NBR NM 45:2006 [23].

2.8. **Visual and microscopic analysis**

Scanning electron microscopy (SEM) was performed for the GBFS and KRS to verify the morphologies and distributions of their particles. Zeiss model EVO MA10 at the Laboratory of Electronic Microscopy and Microanalysis of the IFES Campus Vitória was used. In addition, Energy Dispersive Spectroscopy (EDS) was performed on the GBFS and KRS samples to spectrally evaluate their elemental composition and identify their constituent elements. These spectra can provide a semi-quantitative characterization of the samples.

2.9. **pH determination**

The pH of the slags was determined according to ABNT NBR 10.004 [24] in the Environmental Laboratory of ArcelorMittal Tubarão. Two determinations were made for each material and their arithmetic averages were calculated.

2.10. **Grinding**

To grind the KRS, empirical tests were performed using a Marconi ball mill of the Laboratory of Ceramics of the IFES campus Vitória. The slags were placed in a steel jug internally coated with high alumina, with an internal diameter of 17 cm and a length of 23 cm, and the grinding bodies (balls) used were also made of high alumina. The time, ball size, and rotation speed were varied to allow the slag fineness to satisfy the criterion established in ABNT NBR 16697 [25], according to which at most 8% of the residue may remain in a 75-μm-sieve. After each milling test, the slag was sieved at 150 μm and 75 μm to evaluate the grinding efficiency.

A second test step was performed in the laboratory mill of an Engines Segor model B10 of a cement factory located in southeast Brazil, and the characteristics obtained are described in Table 3.

3. **Results and discussion**

3.1. **Chemical analysis**

The results of the KRS and GBFS chemical analyses are presented in Table 4.

<table>
<thead>
<tr>
<th>Substance</th>
<th>GBFS (wt.%)</th>
<th>KRS (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total CaO</td>
<td>42.8</td>
<td>47.8</td>
</tr>
<tr>
<td>Loss on fire</td>
<td>–</td>
<td>18.3</td>
</tr>
<tr>
<td>Total Fe</td>
<td>0.79</td>
<td>16.0</td>
</tr>
<tr>
<td>SiO₂</td>
<td>37.0</td>
<td>12.3</td>
</tr>
<tr>
<td>Fe</td>
<td>0.51</td>
<td>6.74</td>
</tr>
<tr>
<td>FeO</td>
<td>0.54</td>
<td>6.66</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>10.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Total C</td>
<td>0.17</td>
<td>4.2</td>
</tr>
<tr>
<td>MgO</td>
<td>5.91</td>
<td>3.8</td>
</tr>
<tr>
<td>Total S</td>
<td>1.04</td>
<td>1.25</td>
</tr>
<tr>
<td>MnO</td>
<td>0.37</td>
<td>1.04</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>–</td>
<td>0.24</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.29</td>
<td>0.12</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.34</td>
<td>0.034</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.0019</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

Based on the results, the GBFS is basically composed of CaO, SiO₂, Al₂O₃, and MgO, representing 96.31% of the mass, with residual contents of other oxides in addition to a low percentage of total iron. In case of the KRS, 75.06% of the mass is composed of CaO, SiO₂, Al₂O₃, and MgO, with an additional 16% total iron, of which 6.74% is Fe⁺, and a fire loss of 18.3%. The amounts of SiO₂, Al₂O₃, and MgO are much lower in the KRS than in the GBFS, whereas the CaO content is higher in the former. Based on the CaO/SiO₂ ratio, the slag is classified as basic (>1) or acid (<1). For the GBFS, the CaO/SiO₂ ratio is 1.16, and for the KRS it is 2.99, and thus, both are basic.
Although the GBFS and KRS constituents are practically the same, they differ in content because of the type of manufacturing process: the GBFS is a by-product of pig iron production (in a blast furnace), whereas the KRS is a by-product of pig iron desulfurization (in the Kambara reactor).

The chemical analysis of the CP III 40 cement purchased for the execution of the research is presented in Table 5.

### 3.2. Mineralogical analysis by X-ray diffraction

The GBFS X-ray diffractogram is shown in Fig. 2. The GBFS is predominantly amorphous, exhibiting only a crystalline peak at 2θ = 30° relative to Ca(OH)$_2$; in comparison, at other diffraction angles (2θ) it behaves amorphously.

Fig. 3 shows the KRS X-ray diffractogram and reveals that the KRS is crystalline, with primary peaks of Ca(OH)$_2$, graphite, CaCO$_3$, and Ca$_2$SiO$_4$. This crystalline structure reduces the hydraulic activity [12,26,27].

### 3.3. Thermogravimetry (TG) and differential scanning calorimetry (DSC)

Figs. 4–6 show the TG and DSC results of the KRS, GBFS, and CP III cement, respectively.

Fig. 4 shows the differential thermal analysis exhibiting three endothermic peaks in the thermolysis curve associated with mass losses. The first is near 100 °C, characterizing loss of humidity, the second is between 350 °C and 500 °C, indicating the dehydration of Ca(OH)$_2$, and the third peak is between 600 °C and 700 °C, which characterizes CaCO$_3$ decomposition into CaO and CO$_2$. Based on the mass loss percentage, the percentages of Ca(OH)$_2$ and CaCO$_3$ present in the sample were calculated, as done in [21].

Considering the stoichiometry of the dehydration reaction of Ca(OH)$_2$, presented in Eq. [1], and the molar masses of the reagent and products, for each 74.1 g of Ca(OH)$_2$, 18 g H$_2$O was...
released, with the Ca(OH)₂ mass being 4.11 times higher than the mass of water released. Thus, the percentage of the mass loss between 350 °C and 500 °C was multiplied by a factor of 4.11 to determine the Ca(OH)₂ content.

\[
\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O} \quad (1)
\]

\[
\%\text{Ca(OH)}_2 = 3.14\% \times 4.11 = 12.91\% \quad (2)
\]

Similarly, based on the mass loss between 700 °C and 800 °C and decomposition reaction of calcium carbonate (CaCO₃) (Eq. [3]), the percentage of CaCO₃ present in the sample was calculated (Eq. [4]).

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 \quad (3)
\]

\[
\%\text{CaCO}_3 = 4.72\% \times 2.27 = 10.71\% \quad (4)
\]

Other calcium compounds likely present in the sample were CaSO₄ owing to the desulfurization of the pig iron, and free CaO, as a function of the excess lime used in the desulfurization process.

Analyses of the thermolysis curve in Fig. 5 reveal that the GBFS slag has a slight and constant mass gain associated with the energy released throughout the test, which is more pronounced at 800 °C.

According to Fig. 6, cement CP III suffers from a small mass loss at approximately 100 °C and 600 °C, whereas in other instances it slightly gains mass. We can attribute the mass gain to the presence of the GBFS in the CP III composition because the GBFS exhibits a similar behavior in Fig. 5.

### 3.4. Granulometric Analysis

The granulometric distribution results of the GBFS and KRSs are shown in Figs. 7–10.

Figs. 7 and 8 exhibit that the KRS has 21.16% particles that are smaller than 150 μm, which is much larger than the value of 3.00% for the GBFS. In comparison, 85% of the GBFS particles are smaller than 1.18 mm, whereas slightly more than 70% of the KRS particles are in this range.

The fineness modulus was calculated according to ABNT NBR NM 248:2003 [22], adding the retained mass percentages accumulated in the normal-series sieves and dividing by 100. The results were 2.34 and 2.54 for KRS and GBFS, respectively. Comparing the results in Table 6, both the KRS and GBFS fall in the optimal range of the granulometric distribution of fine aggregates for concrete.

The maximum characteristic size corresponds to an opening in millimeters of the mesh, in which the accumulated retained percentage of the material is ≤5%. For the KRS, the maximum characteristic size obtained is 4.75 mm, and for GBFS it is 2.36 mm.

For the KRS analysis, according to Fig. 8, d₀.₁ = 15.854 μm, d₀.₅ = 68.198 μm, and d₀.₉ = 156.193 μm, implying that 10% of the fraction smaller than 150 μm is less than 15.854 μm, 50% lower than 68.198 μm, and 90% lower than 156.193 μm. The specific area of this fraction of the sample is 0.307 m²/s.

The analysis of the fractions in 150 μm of the GBFS (Fig. 10) yield values of d₀.₁ = 36.575 μm, d₀.₅ = 119.932 μm, and d₀.₉ = 267.780 μm, in addition to a specific area of 0.0917 m²/s. The d₀.₁, d₀.₅, and d₀.₉ of the GBFS are larger than those of the KRS, which corroborates with the smaller specific area.

Considering that the cement industry utilizes particle sizes smaller than 75 μm, it is necessary to perform mechanical
Fig. 8 – Determination of the GBFS granulometry before milling.

Fig. 9 – Granulometric distribution of the KRS through 150 μm.

Fig. 10 – Granulometric distribution of the GBFS through 150 μm.

**Table 6 – Limits of the granulometric distribution of the fine aggregates [33].**

<table>
<thead>
<tr>
<th>Sieve with mesh opening</th>
<th>Lower limits</th>
<th>Retained mass percentage</th>
<th>Upper limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Usable zone</td>
<td>Optimal zone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Optimal zone</td>
</tr>
<tr>
<td>9.5 mm</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6.3 mm</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4.75 mm</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>2.36 mm</td>
<td>0</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>1.18 mm</td>
<td>5</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>600 μm</td>
<td>15</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>300 μm</td>
<td>50</td>
<td>65</td>
<td>85</td>
</tr>
<tr>
<td>150 μm</td>
<td>85</td>
<td>90</td>
<td>95</td>
</tr>
</tbody>
</table>

Notes: (1) The fineness modulus of the optimal zone varies from 2.20 to 2.90; (2) The fineness modulus of the lower usable zone ranges from 1.55 to 2.20; (3) The fineness modulus of the upper usable zone ranges from 2.90 to 3.50.
activation through grinding. Because the slag is comminuted, silicon chains will be destroyed, activating the oxygen ions bound to them, and thus, accelerating the dissolution rate of the slag, followed by precipitation of the hydrated products [28–30].

3.5. Unit weight

The unit weight of the GBFS and KRS was determined by Kaeme Engenharia following the requirements of the ABNT NBR NM 45 standard [23]. The values used to determine the unit weight are described in Table 7. The mass value of the most aggregated vessel refers to the average of three weights. The KRS is denser than the GBFS, an expected result because the KRS is composed of a higher percentage of iron.

3.6. Visual and microscopic analysis

The SEM results for the GBFS and KRS are shown in Figs. 11 and 12, respectively.

The KRS by-product shown in Fig. 12 has smaller particles, offering a larger specific area and causing the particles to aggregate, than the GBFS by-product particles (Fig. 11). Morphologically, the GBFS particles are polygonal and spherical (Fig. 11), whereas the KRS by-product particles are more spherical shapes, with a larger number of aggregates than in the former (Fig. 12).

In addition, EDS is performed for the GBFS and KRS samples to spectrally evaluate their elemental composition to identify their elements, thus providing a quantitative characterization of the samples. Fig. 13 illustrates the locations selected for the EDS and spectra 2, 3, and 4 of the GBFS by-product.

By EDS, O, Ca, Si, Al, and Mg are detected in the GBFS by-product, with O, Ca, and Si having the highest percentages. This corroborates the chemical analysis tests.

A similar analysis was performed for the KRS. The sites selected for the EDS and spectra 8 and 9 for this by-product are shown in Fig. 14. Because the KRS sample is more agglomerated, only two points are used when conducting the EDS test.

For the KRS, the chemical elements present in spectra 8 and 9 are O, Ca, Si, and Al, with O and Ca present in the highest percentages. These values corroborate the chemical analysis and X-ray diffraction tests for the by-product.
3.7. pH

The slag pH was determined according to ABNT NBR 10004 [24] in the ArcelorMittal Tubarão Environmental Laboratory, and the results are provided in Table 8. The final pH results are the arithmetic averages of two measurements per slag type.

The results show that the KRS is more alkaline than the GBFS. The higher pH of the KRS implies more OH⁻ ions are available when added to water, corroborating the TG result that showed 12.91% Ca(OH)₂ in the KRS. The hydration of the GBFS in water occurs very slowly owing to the formation of a film lacking Ca²⁺, which inhibits the advance of hydration [31]. In contrast, the presence of hydroxyl facilitates the elution of Ca²⁺, Si⁴⁺, and Al³⁺ ions from the GBFS, contributing to the advancement of hydration [21]. Thus, the KRS might contribute to GBFS activation in the cement hydration process, so that they could be used together to produce Portland cement.

3.8. Grinding

As mentioned above, CP III cement was used as a base for preparing the blends. Because the GBFS is already a constituent of CP III cement and is already widely used and standardized for such applications, the grinding test was performed only for the KRS.

For the grinding of the KRS, empirical tests were performed using a Marconi ball mill from the Ceramics Laboratory of the IFES Campus Vitória. A steel jug internally coated with high alumina was used, with an internal diameter of 17 cm and a length of 23 cm. The grinding balls were also made of high alumina. The time, ball size, and speed of rotation were varied to ensure the ground slag fineness conformed to the criterion established in ABNT NBR 16697 [25], according to which at most 8% of the retained product in sieve 200 with opening 75 μm, can be retained. The grinding conditions of the tests are provided in Table 9.

Calculations of the total ball mass, ball size distribution, and sample mass were performed according to the Herbst-Fuerstenau model [32].

All the beads were placed in a jar together with the sample to perform each of the grindings denoted as #1, #2, #3, and #4. At the end of the first grinding, the sample was still visually coarse, so that sieving was not performed to evaluate the fineness. After three millings while varying the time and frequency, a significant amount of material was retained in the 0.15-mm and 0.075-mm-sieves. The fourth test was performed by reintroducing a part of the test #3 sample for another 4 h of milling, but the result was not satisfactory because the sum of the percentages retained in the 0.15-mm and 0.075-mm-sieves was higher than that for test 3. Thus, there was some error in the sifting process. In tests 5 and 6, milling was performed in three steps. At each step, the total mass of the single-sized balls was determined, starting with the larger 32-mm-balls, followed by the 19-mm and 13-mm-balls, respectively. Each milling lasted for 1 h in test 5 and 2 h in test 6. Milling in stages favored the reduction in the percentage of KRS retained in the 0.15-mm-sieve, but the sum of the total retained percentage remained high, and the best result was achieved in test 3, with 49.5% of slag higher than the percentage for the 0.075-mm-sieve.

After various millings under different conditions, the equipment used at laboratory scales was not efficient for

### Table 8 – pH analysis results for the GBFS and KRS.

<table>
<thead>
<tr>
<th>Slag</th>
<th>Average pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>GBFS</td>
<td>10.310</td>
</tr>
<tr>
<td>KRS</td>
<td>12.251</td>
</tr>
</tbody>
</table>

### Table 9 – Grinding tests of the GBFS and KRS by-products. Each grinding test is described because of the different conditions used in each test.

<table>
<thead>
<tr>
<th>Test</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balls (mm)</td>
<td>32</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3397</td>
</tr>
<tr>
<td>mass (g)</td>
<td>19</td>
<td>1799</td>
<td>1800</td>
<td>1800</td>
<td>1800</td>
<td>3384</td>
</tr>
<tr>
<td>(g)</td>
<td>13</td>
<td>1583</td>
<td>1583</td>
<td>1580</td>
<td>1580</td>
<td>3380</td>
</tr>
<tr>
<td>Sample (g)</td>
<td>1064</td>
<td>1064</td>
<td>1065</td>
<td>520</td>
<td>1064</td>
<td>1065</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>30</td>
<td>30</td>
<td>45</td>
<td>45</td>
<td>45</td>
<td>30</td>
</tr>
<tr>
<td>Rotation (RPM)</td>
<td>234</td>
<td>234</td>
<td>351</td>
<td>351</td>
<td>351</td>
<td>234</td>
</tr>
<tr>
<td>Time (h)</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>10</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Held in #0.15 mm (%)</td>
<td>–</td>
<td>49.5</td>
<td>44.5</td>
<td>56.8</td>
<td>38.5</td>
<td>39.2</td>
</tr>
<tr>
<td>Held in #0.075 mm (%)</td>
<td>–</td>
<td>25.9</td>
<td>5.0</td>
<td>25.1</td>
<td>23.7</td>
<td>23.4</td>
</tr>
<tr>
<td>Accumulated retention (%)</td>
<td>–</td>
<td>75.4</td>
<td>49.5</td>
<td>81.9</td>
<td>62.2</td>
<td>62.6</td>
</tr>
</tbody>
</table>
grinding the KRS. Thus, a partner company, a cement manufacturer, was contacted to help in the grinding of this by-product.

The KRS was crushed prior to milling to ensure the input particles were smaller than 3.5 mm, and then 1 kg of the KRS was inserted into the mill along with the total ball load. The grinding process was performed using clinker grinding parameters to achieve a maximum of 11% retention in sieve 325 (0.045 mm), and maintaining a fixed rotation speed, 4000 turns were performed. The slag was then sieved and 40% was retained in the 325 mesh, whereas the 200-mesh retained 23%.

The results of the last milling test showed an evolution relative to the previous results presented in Table 1, probably owing to the use of steel grinding bodies, which have a higher density than that of alumina, improving comminution. However, the result did not meet the cement standard requirement when evaluating the KRS alone, but considering that the additions are at most 30% KRS, it is expected that mixtures using this type of slag can be framed with the standard.

4. Conclusions

In this study, the KRS had a considerably lower concentration of SiO₂, Al₂O₃, and MgO and higher percentage of total Fe and Fe⁺ compared to those of the GBFS. In addition, the KRS had a fire loss of 18.3%, a behavior not identified for the GBFS.

The GBFS was predominantly amorphous, whereas the main phases present in the KRS were Ca(OH)₂, graphite, CaCO₃, and Ca₂SiO₄.

Based on the TG, it was estimated that the KRS had 12.91% Ca(OH)₂ and 10.71% CaCO₃. However, the GBFS showed a slight and constant mass gain associated with the release of energy throughout the test, possibly owing to crystallization and oxidation, and some decomposition reactions occurred that were exothermic.

The KRS had a maximum characteristic particle size of 4.75 mm, whereas the GBFS particles were at 2.36 mm. Based on the fineness modulus (2.34 and 2.54 for the KRS and GBFS, respectively), both the KRS and GBFS fineness values were classified in the optimal zone according to ABNT NBR 7211:2005 [33].

The KRS had a specific area of 0.307 m²/g and the GBFS had 0.0917 m²/g, in the final fraction of 150 μm (21.16% of the KRS and 3.00% of the GBFS).

It was necessary to perform mechanical activation by grinding the slag because the cement industry works with particle sizes smaller than 75 μm.

The KRS had a unit weight larger than that of the GBFS (1437.47 kg/m³ and 1196.12 kg/m³, respectively), which was already expected owing to the higher total iron content of the KRS.

In the SEM analyses, the predominantly spherical KRS particles aggregated more than the GBFS particles, which had polygonal and spherical morphologies.

The KRS was more alkaline than the GBFS, which may have contributed the OH⁻ ions in the cement hydration process.

The grinding of the KRS using the Marconi equipment with alumina balls was not efficient possibly owing to the lower density of the balls compared to that of the steel balls.

The grinding of the KRS using the same clinker milling conditions (BB10 mill with steel balls) was more efficient, reaching 23% of material retention in a 75-μm sieve. However, the fineness modulus required for the clinker was not reached for the KRS.

Thus, it was concluded that KRS is a by-product that offers the possibility of use for the manufacture of Portland cement, although it will be necessary to perform thermal, mechanical, or chemical activations so that the cement requirements are reached.

Conflicts of interest

The authors declare no conflicts of interest.

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