Original Article

Preparation of glaze using electric-arc furnace dust as raw material

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A R T I C L E   I N F O

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A B S T R A C T

Large industrial productions generate large amounts of waste, and researchers are investigating alternatives to reuse them. For instance, these wastes can be used to produce ceramic pigments in the ceramic tile industry. Electric-arc furnace dust (EAFD) is waste generated in the steelmaking process through the volatilization of metals from scrap and exhibits great potential for its use as a raw material in the production of ceramic pigments. The aim of this study is to produce glazes containing EAFD for ceramic tiles. The EAFD was characterized via laser diffraction, wavelength-dispersive X-ray fluorescence (WDXRF) spectroscopy, X-ray diffraction (XRD), thermogravimetric (TG), and differential thermogravimetric (DTG) analyses. Two glaze types (BGS and CBT) were produced with 2, 4, 6, and 8 wt.% EAFD and characterized via the Commission Internationale de l’Éclairage (CIE) L*a*b* values, abrasion resistance, and XRD. According to the particle size distribution analysis, the average particle size of the EAFD is 0.770 μm. Further, the chemical WDXRF analysis revealed that 44.60% of the EAFD is iron oxide and 26.24% is zinc oxide. According to the structural XRD analysis, the major crystalline phases of the EAFD are zinrite, franklinite, magnetite, and other phases with spinel structures. The EAFD exhibits stability close to the firing temperature of the ceramic tiles (1130°C). In addition, the ceramic tiles coated with both glazes became darker with increasing EAFD amount. These samples obtained a PEI 3 rating based on the abrasion analysis.

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1. Introduction

The increasing industrial productions generate annually several tons of dust, slag, sludge, exhaust gases, and wastewater. In some cases, the wastes are inappropriately disposed of in the environment and may damage the environment and population [1–6]. Many studies have reused these wastes to reduce their environmental impact. Regarding the ceramic industry, the wastes are used in ceramic products processed at high temperatures because the heat treatment allows the neutralization of hazardous elements [1]. However, the potential of the waste is still not fully exploited. Another way to reuse wastes is to employ them as pigments for ceramic tiles because they are rich in metallic elements that provide different colors for inks and glazes [1–8].

Costa et al. used sludge from chemical stripping processes of drawn steel to produce ceramic pigments via the solid-state reaction. The result is a completely achronomictic pigment with low luminosity. Ink including 5% of this pigment exhibited an excellent quality [1]. Moreover, Shen et al. used a mixed solution of ferrous and ferric sulfate leached from a blast furnace to prepare nanometric pigments of magnetite via the coprecipitation method. The resulting pigment had a low spectral reflectance, narrow size distribution, and very intense black color [3]. Metallurgical by-products were employed by Ovčačíková et al. as pigment for the preparation of ceramic glazes and engobes. The different calcination temperatures of the metallurgical by-products resulted in glazes with different colors, such as brown and brown-yellow tones. The engobes prepared from the by-products exhibited grey and red tones [4].

Regarding steelmaking with electric-arc furnaces (EAFs), the crude steel production was 472,696 million tons in 2017 (World Steel Association, 2018). However, it is estimated that 1–2 wt.% of the steel produced in the EAF generates dust known as electric-arc furnace dust (EAFD) [9–11]. In the EAF steelmaking process, the steel scrap is used as metallic charge and its melting is realized through an electric arc that forms a short circuit between the graphite electrodes and scrap. At this stage, the metals are volatilized owing to the high temperature in the furnace [12,13]. The volatilized metals are segregated in the baghouse owing to the negative pressure created by the EAF exhaust system. Hence, the particles are drawn into a precipitator in which the larger particles are collected and the finer particles (EAFD) are fed into the dedusting system [13].

According to the Brazilian standard ABNT NBR 10004/2004 and European Waste Catalogue (EWC 2002), EAFD is hazardous waste owing to the presence of heavy metals such as chromium, lead, and cadmium [9,10,14]. Therefore, the disposal costs of this waste are very high; 200 million dollars are annually spent to dispose this waste in the United States [14]. Thus, the EAFD has been reused in structural ceramics (blocks) [15], glass [16] and glass-ceramic materials [17], red ceramic for building construction [18], asphalt cement for road construction [19], mortars [20], etc. However, EAFD comprises other metal compounds, such as zinc (up to 40 wt.%) and iron (up to 50 wt.%), which can be recovered and reused [9]. The presence of high levels of zinc occurs owing to the use of galvanized automobile scrap [10,21]. However, this dust cannot return to the steelmaking process via sintering because the zinc vapor can deposit on the walls of blast furnaces, thereby forming incrustations, decreasing the iron amount, generating more gases, heating the pipes of the cleaning system by re-oxidation with air, and generating more dust [12]. Furthermore, the dust cannot be used as raw material in the EAF because it increases the energy consumption [11].

It is necessary to investigate other ways to reuse this waste. Some studies have demonstrated that EAFD exhibits different crystalline phases; i.e., hematite and magnetite [9,11,14,23,22]. According to ref. [5,7,24], the hematite and magnetite phases can result in red and black pigments, respectively. Besides that, EAFD has small particle sizes; The majority of particle sizes measures less than 20 μm [13], and the ideal size range for materials used as ceramic pigments is approximately 5 μm [4,25]. These chemical and structural characteristics make EAFD a promising candidate to be used as raw material in the pigment production. This study investigates the production of glazes containing EAFD for ceramic tiles to minimize the harmful environmental effects of its inappropriate disposal.

2. Experimental

2.1. Materials

The EAFD was obtained from Siderúrgica Norte Brasil S.A. (SINOBRA). The commercial glazes CBT-5213 and BGS-9007 were from Colorminas – Colorificio e Mineração S.A. and Torreid Brasil Ltda., respectively. The engobe was from RochaFortê Comércio e Indústria Ltda. and Colorobbia Brasil Ltda. The glazes, engobes, and clays for the ceramic bodies were donated by Cerâmica Sergipe Indústria e Comércio Ltda. (Escurial).

2.2. Treatment of electric-arc furnace dust (EAFD)

Initially, an EAFD suspension was prepared and sieved through a 325 mesh. The suspension was homogenized via planetary ball milling (Retsch PM 100) for 60 min under 250 rpm and then dried in an oven (Brasdonto) without air circulation at 100 ± 10 °C for 48 h.

2.3. Sample preparation

The treated EAFD was added to the glazes (CBT-5213 and BGS-9007) with weight concentrations of 2, 4, 6, and 8 wt.% and applied to the ceramic bodies through a manual serigraphic screen (Servitech CT-105). Next, the samples were fired at 1130 °C for 23 min in a roller hearth furnace (SITI) in an industrial environment. The BGS-9007 glaze samples with 0, 2, 4, 6, and 8 wt.% EAFD were called BGS-0, BGS-2, BGS-4, BGS-6, and BGS-8, respectively. The CBT-5213 glaze samples with 0, 2, 4, 6, and 8 wt.% EAFD were called CBT-0, CBT-2, CBT-4, CBT-6, and CBT-8, respectively. Fig. 1 illustrates the experimental process.

2.4. Characterization methods

The specific gravity of the EAFD was determined via the international standard ASTM D 854-14. The specific gravity (Gs)
rears to the relation between the density of the solids (\(\rho_s\)) and the density of water at the test temperature (\(\rho_{w,t}\)) [26]:

\[
G_t = \frac{\rho_s}{\rho_{w,t}}
\]

According to ASTM D 854-14, the density of water (\(\rho_w\)) changes with the temperature (t). Hence, it is necessary to calculate the specific gravity as a function of the temperature:

\[
G_t = \frac{M_5}{(M_{\text{w,t}} - (M_{\text{w,t}} - M_3))}
\]

Where:

- \(M_5\) = mass of the oven dry solids (g);
- \(M_{\text{w,t}}\) = mass of the pycnometer and water at the test temperature \(T_t\) (g);
- \(M_{\text{w,t}}\) = mass of pycnometer, water, and solids at the test temperature \(T_t\) (g).

The \(G_t\) value is non-dimensional. Besides, the specific gravity is calculated for a water temperature of 20°C (\(G_{20^\circ C}\)). Hence, a temperature coefficient (K) correlates the density of water at temperature t to the density of water at 20°C based on ASTM D 854-14. The specific gravity of EAFD at 20°C is calculated via:

\[
G_{20^\circ C} = K \cdot G_t
\]

Where:

\[K = \frac{\rho_w}{0.9982063}\]

The specific gravity of EAFD was fed as sample information into the Malvern HYDRO 2000MU laser granulometer. Distilled water was used as dispersant, and ultrasound and sodium lauryl ether sulfate deflocculant were used to disperse the dust in water. The chemical compositions of EAFD and glazes were studied by wavelength-dispersive X-ray fluorescence (WDXRF) spectroscopy in a Bruker S8-Tiger 4 kW spectrometer equipped with LiF 200, PET, XS-5 and XS-C crystals. The analyses were performed under vacuum using pressed pellets without addition of boric acid. The relative concentration of the elements was calculated considering their respective oxides. Moreover, the crystalline structures of EAFD and glazes were determined using the Bruker D8 Advance X-ray diffractometer (XRD) with Cu Kα1 radiation (\(\lambda = 1.5418\ \text{Å}\)), voltage of 40 kV and current of 40 mA. The scanning range covered 10°–70° 2θ, step of 0.02° 2θ and fixed counting time of 0.3 s. The data treatment was
performed with the Match! 12.0 software and JCPDS-ICDD database files.

The thermogravimetric (TG) and differential thermogravimetric (DTG) analyses were performed using the NETZSCH STA 449 F1 Jupiter apparatus with a heating rate of 10 °C.min⁻¹ up to 1200 °C. The abrasion resistance of the samples after sintering was evaluated according to the Brazilian standard ABNT NBR 13818. The samples with dimensions of 10 × 10 cm were subjected to the Servitech CT-247 abrasimeter. Additionally, a colorimetric analysis was performed using the NCS digital colorimeter RM200 with geometry 45°:0°. The Commission Internationale de l’Éclairage (CIE) chromatic coordinate system L’、“a”b” was used to evaluate the sample colors after sintering.

3. Results and discussion

3.1. EAFD characterization

Tables 1 and 2 list the data and results for the specific gravity analysis, respectively. The specific gravity value of EAFD (4.138 ± 0.001 g.cm⁻³) is very similar to the value found in literature. For instance, Fedorko et al. [27] determined a specific gravity of 4.33 g.cm⁻³. Further, Nolasco–Sobrinho et al. [28] observed that the specific gravity of EAFD depends on the location in which the EAFD was collected; EAFD collected in a mixing chamber had a specific gravity of 4.90 g.cm⁻³, and EAFD collected in a baghouse had a specific gravity of 4.38 g.cm⁻³. The latter specific gravity value is very similar to the one determined in this study (also collected in a baghouse).

Additionally, Mantovani et al. [29] observed that four different EAFD samples collected in a baghouse had four different specific gravities (2.96 g.cm⁻³–4.12 g.cm⁻³). These are due to elements with different densities and the chemical compositions, which change with the metallic charge. For instance, zincite and magnetite have densities of 5.6 and 5.2 g.cm⁻³, respectively. However, other elements with lower densities exist, and occluded pores also alter the specific gravity.

Fig. 2 presents the particle sizes and particle size distributions determined with the laser granulometer. The axes (left and right) show the statistical weight of each particle size class (particle size distributions). Particle size distributions can be represented either in differential form as frequency curves (left axis) or, more precisely, probability density distributions and in integral form as cumulative curves (right axis) [30]. The peak of the frequency curve is the mode. The mode represents the particle size most commonly found in the distribution. There is more than one peak for the distribution in Fig. 2. Therefore, more than one heavy density region is present in which case the distribution is said to be bimodal [31].

The particle sizes range from 0.1 μm to 10 μm, which corroborates with ref. [29]. According to Mantovani et al. [29], most individual EAFD particles are smaller than 10 μm. However, some particles are larger than 10 μm because very fine particles become agglomerated and form particle aggregates. Another factor that influences the particle size distribution is the air moisture; the particles agglomerate through hydration reactions. Further, the storage manner influences the particle size distribution. However, Guézenne et al. [13] demonstrated that most individual EAFD particles are smaller than 20 μm. A small part of these fine particles is monocrystalline zinc oxide. The major part is spherical particles of a slag phase and steel phase enriched in zinc.
Moreover, Fig. 2 presents the cumulative numbers of particles (cumulative curve). According to the results, 90% of particles are smaller than 4.771 μm, 10% are smaller than 0.156 μm, and 50% are smaller than 0.770 μm (average particle size). The determined average EAFD particle size is smaller than those found in ref. [14,22,29]. The specific surface area of EAFD was also calculated by laser granulometer as 15.4 m² g⁻¹. This value is larger than the results found by Mantovani et al. (0.59 m² g⁻¹-5.09 m² g⁻¹) [29]. Studying the particle size is crucial because conventional ceramic pigments must have particle sizes of approximately 5 μm [4,25]. Further, the optical properties of ceramic pigments depend on the particle size. The light absorption increases with decreasing particle size down to approximately 0.4 μm. Below 0.4 μm, it remains constant. The light scattering increases with decreasing particle size until a maximum is reached that corresponds to a half wavelength [32].

Table 3 lists the chemical EAFD composition in the form of oxides determined by wavelength-dispersive X-ray fluorescence (WDXRF) spectroscopy. The dust is a simultaneous result of evaporation and oxidation of various metals, capture of low-density furnace additives, and ejection of particulates from slag and metal [10,13]. The dust composition is remarkably variable because it depends on the gas composition in the freeboard of the EAF, the operating parameters of the furnace, conditions in the off-gas handling system [10], and scrap composition used in the EAF [9,10,14,21]. The scrap used in the EAF is automobile scrap containing galvanized steel and therefore zinc [10,14,22]. The zinc amount depends on the galvanized steel scrap and can occupy up to 40 wt.% in the EAFD [9,14]. In the presented EAFD, a zinc oxide amount of 26.24% appears in the gas phase because the boiling point of zinc (907 °C) is lower than the typical operating temperature of the steelmaking process (1600 °C). The iron oxide is the compound with the highest amount (44.60%) in the EAFD. It appears in its gas phase owing to the direct evaporation or indirect bursts of gas bubbles [10].

The presence of sulfur and halogen in the EAFD (e.g., chlorine and bromine) is due to a carry-over of material from the reactor furnace to the dust, which depends on the process stability and operation conditions [29]. Further, calcium oxide and magnesium oxide are present in the dust because they are added in the furnace as desulfurizing agents during the final phase of the steelmaking process [12,14]. The EAFD contains manganese oxide because most commercial automobile steels contain small percentages of manganese (0.3%–0.8%). Because manganese is more volatile than iron at 1400 °C–2100 °C, the manganese-to-iron ratio of the dust can be significantly higher than that of the steel [10]. The presence of tin in the dust is because tin-coated scrap (tinned steel) can also be used in the furnace. Generally, the scrap contains impurities such as copper, lead and nickel because these elements are nobler than iron and cannot be eliminated by selective oxidation during the oxidizing phase of the steelmaking process. Other impurities are sulfur and phosphorus. Their elimination requires special conditions of high basicity. Other present less harmful elements in the steel and consequently in the EAFD are, e.g., aluminum, titanium, chromium, and silicon [12].

Fig. 3 presents the XRD characterization of the EAFD. Minerals based on iron and zinc oxides are the main components. Iron is presented by the following crystalline phases: calcium iron oxide, magnetite, and franklinite. Further, zinc is presented by zincite and franklinite phases. Others crystalline phases are, e.g., calcium iron oxide, quartz, and sylvite. The latter is poorly crystalline, but it is present because chlorine presents a percentage of 5.01% in the chemical EAFD composition (Table 3), which is detectable by Bruker D8 Advance X-ray diffractometer. Franklinite, magnetite, quartz and zincite are the most common phases reported in literature. All crystalline EAFD phases of this study are in a good agreement with the results in ref. [11,14,15,18,20,22,23,28,29,33].

The zinc in the dust can react with oxygen to form zinc oxide or with iron and oxygen to form zinc ferrite (franklinite). The amount of zinc oxide increases with increasing zinc amount in the EAFD. However, the amount of franklinite in the EAFD decreases with increasing zinc-to-iron ratio [10]. The formation of franklinite (ZnFe₂O₄) occurs through two mechanisms and starts from pure iron droplets and zinc vapor in the off-gas. In the first mechanism, franklinite is produced via the precipitation of zinc oxide particles on an iron oxide layer. Hence, a solid–solid chemical reaction occurs between these two oxides and oxidized particles with spinel rings on the outside are formed. In the second mechanism, franklinite is produced via a zinc vapor reaction with iron oxide through a gas–solid chemical diffusion reaction. Hence, a further reaction of the particles with oxygen results in fully oxidized particles with a zinc concentration gradient from the edge to the center of the particles [21].

The magnetite phase (Fe₃O₄) is an inverse spinel phase and contains both divalent and trivalent iron. Magnetite is known as black pigment because its light absorption is much greater than the light scattering for the entire visible range. The most important optical properties of iron oxides as pigments are the light scattering and absorption coefficients. Both coefficients depend on the particle size and refractive index. The
latter depends on the wavelength of the light, illuminant, and viewing direction toward the anisotropic iron oxides. However, magnetite is isotropic. Thus, it has only one refractive index: 2.42. Furthermore, the light scattering and absorption coefficients determine pigment properties such as hiding power and tinting strength, which are important properties in the paint industry. The tinting strength measures the capacity of a pigment to transmit color to other light scattering materials. The smaller the particle size and the wider the particle size distribution, the greater is the tinting strength of a powder. For example, the tinting strength of magnetite increases although the average particle size remains constant because the particle size distribution continues to decrease [24].

As magnetite, other phases such as franklinite and calcium iron oxide have spinel structures. The peaks (18.23°, 29.94°, 35.27°, 36.92°, 42.96°, 53.17°, 56.66° and 62.19° 2θ) of all these phases overlap, as shown in Fig. 3. This behavior was also observed in ref. [14,22,23,29]. The phases with equal structure occur because iron oxides have isostructural equivalents in which cations other than iron occupy the interstices of the oxygen framework. In the magnetite phase, the substitution of a large range of cations can be induced because tetrahedral and octahedral positions are available. The probability of a substitution depends on the similarity of the ionic radii and valency of the cations. The following cations replace iron in magnetite: Al^{3+}, Mn^{2+}, Zn^{2+}, Ca^{2+}, Ni^{2+}, Cu^{2+}, and Co^{2+} [24].

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Phase</th>
<th>Formula</th>
<th>ICDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Sylvite</td>
<td>KCl</td>
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</tr>
<tr>
<td>Z</td>
<td>Zincite</td>
<td>ZnO</td>
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<tr>
<td>CIO</td>
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<td>Ca0.15Fe2.85O4</td>
<td>PDF-2: 046-0291</td>
</tr>
<tr>
<td>Q</td>
<td>Quartz</td>
<td>SiO2</td>
<td>PDF-2: 078-2315</td>
</tr>
<tr>
<td>M</td>
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<td>Fe3O4</td>
<td>PDF-2: 072-2303</td>
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<tr>
<td>F</td>
<td>Frankline</td>
<td>ZnFe2O4</td>
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</tr>
</tbody>
</table>

**Fig. 3 – XRD characterization of EAFD.**

**Fig. 4 – TG and DTG analyses of EAFD.**

The presence of elements such as zinc and calcium in EAFD provide the formation of these ferrites, as shown in Fig. 3. Fig. 4 presents the results of the TG and DTG analyses of the EAFD. The TG diagram shows three mass loss steps. The first one occurs at 30°C – 380°C and measures approximately 38.8% of the total mass. This loss corresponds to the evaporation of physically adsorbed water (30°C–140°C) and the evaporation...
of chemically adsorbed water (140°C–380°C) [9,14]. The second one occurs at 380°C–1025°C and measures approximately 18.4%. This loss corresponds to the release of carbon dioxide during the decomposition of carbonates at 550°C–800°C [14], the volatilization of metal chlorides at 630°C–700°C [9] and the volatilization of zinc at 907°C [10]. The volatilization of zinc can be observed in the DTG diagram through the peak between 900°C and 1025°C. Besides, in this step the magnetite first turns into maghemite (γ-Fe₂O₃) and then into hematite (α-Fe₂O₃) [24,34] at approximately 550°C [34]. The third mass loss step occurs in the range of 1025°C–1200°C and measures approximately 2.1%. The total mass loss is approximately 59.3%. However, the EAFD was stable close to the firing temperature of the ceramic tiles (1130°C), which is desirable for a material used for pigment production.

3.2. Glaze characterization

Table 3 also lists the data of the chemical glaze composition. Two types of commercial glazes were used in this study. Their differences can be seen in the table. The main difference regarding the chemical composition of both glazes is that the CBT-5213 glaze contains more zinc oxide than BGS-9007. Zinc oxide is frequently used in glaze compositions because it decreases the viscosity and surface tension of the glaze melt, which promotes the spreading of melt over a substrate. Further, zinc oxide improves the chemical resistance of the glaze and reacts with silicon dioxide or aluminum oxide in the melt to form fine crystals after cooling, which form a glass ceramic [35]. Figs. 5 and 6 present the XRD characterization of the BGS-9007 and CBT-5213 glazes with EAFD after sintering, respectively.

According to Fig. 5, the pure BGS-9007 glaze (with 0% EAFD) is amorphous, and the addition of EAFD does not change the glaze structure. According to Fig. 6, the pure CBT-5213 glaze (with 0% EAFD) is a glass ceramic and its crystalline phase is wollastonite (CaSiO₃)—a phase commonly found in glass ceramics that exhibit special optical effects [35]. However, the wollastonite phase decreases with increasing EAFD amount in the glaze. Kavours et al. [17] observed that in the stabilization process of EAFD in a vitreous matrix (silicon dioxide, sodium carbonate and calcium carbonate), the final product exhibits an amorphous matrix when the powders are rapidly cooled down. Further, a crystalline matrix with a wollastonite phase occurs when the powders are heat-treated for 15 min for nucleation and 30 min for a growth process. In this study, the glazes were sintered at high temperatures (1130°C) and the complete cycle (heating and cooling) lasted 23 min in an industrial environment. The complete process is very fast and does not offer the crystals sufficient time to nucleate and grow. Consequently, the glazes have amorphous structures.

3.3. Sample characterization

3.3.1. Abrasion resistance of glazes

Glazes with different EAFD concentrations were applied on ceramic bodies and sintered to evaluate their abrasion resistances. According to the PEI method, the glaze must be subjected to a circular motion with AISI 1020 steel balls of different diameters (1 mm, 2 mm, 3 mm and 5 mm) and 3 g molten white aluminum oxide F80 as abrasive charge. The number of cycles must be in accordance with the Brazilian standard ABNT NBR 13818. First, the glaze must undergo 100 cycles and then another 150, 600, 750, 1500, 2100, 6000, or 12,000 cycles until the glaze exhibits a loss in brightness. Depending on the number of cycles, the glaze is classified according to the PEI rating. The results of the abrasion resistance of the BGS and CBT samples show that both glazes tolerate 1500 cycles without brightness losses. Therefore, their PEI rating is 3 according to the standard. Glazes for ceramic tiles with PEI 3 can be used in residential environments in which they come in contact with certain amounts of abrasive dirt that is not sand and other materials with a hardness greater than that of sand.

Moreover, the abrasion resistance was analyzed using an optical microscope. Figs. 7 and 8 present the results of the BGS and CBT samples after 2100 cycles, respectively. After 2100 cycles, both glazes lose their brightness (light regions), and the engobe layer is evident (dark regions). In Fig. 7, the
Fig. 7 – Abrasion resistance analyzed via optical microscopy of BGS samples after 2100 cycles: (a) BGS-2, (b) BGS-4, (c) BGS-6, (d) BGS-8.

Fig. 8 – Abrasion resistance analyzed via optical microscopy of CBT samples after 2100 cycles: (a) CBT-2, (b) CBT-4, (c) CBT-6, (d) CBT-8.

quantities of light regions on all BGS samples are very similar. Therefore, all BGS samples possess the same PEI rating. These results corroborate with the XRD results in Fig. 5 because all BGS samples (2, 4, 6, and 8% EAFD) present an amorphous diffractogram. By contrast, in Fig. 8, CBT-2 exhibits more light regions than CBT-8. Thus, CBT-2 lost less glaze than CBT-8. These results are in a good agreement with the XRD results in Fig. 6 because the CBT-2 sample exhibits a crystalline phase (wollastonite) commonly found in glass ceramics and is therefore more abrasion-resistant than the other CBT samples. The
CBT-8 sample has an amorphous structure and is therefore less abrasion resistant than CBT-2 [35]. However, all CBT samples possess the same FEI rating.

3.3.2. Color development of glazes

According to the CIE system, in the color space, the +a* axis corresponds to the red color stimuli and −a* corresponds to the green color stimuli. The +b* axis corresponds to the yellow color stimuli and −b* to the blue color stimuli. The lightness L* ranges from 0 (black) to 100 (white) [36]. Table 4 presents the data of the colorimetric analysis according to the CIE system for BGS and CBT. According to Table 4, the lightness (L*) decreases with increasing EAFD amount in the BGS glaze. This result was expected because the EAFD exhibits a dark brown color. The yellow component (+b*) increases with increasing EAFD amount in the BGS samples, whereas the red and green components do not suffer defined variations. According to Table 4, CBT behaves similarly to BGS. However, in CBT, the lightness (L*) decreases less than in BGS. Further, the yellow component (+b*) increases less than in the BGS samples.

Figs. 9 and 10 present the colors of the BGS and CBT samples, respectively. Based on the Natural Color System (NCS), the color codes consist of four digits followed by an alphanumeric code, which relate to the percentages of darkness and saturation. The alphanumeric code is based on pairs that compose the six elementary colors: white, black, yellow, red, blue, and green (Table 4). For both glazes (BGS and CBT) with 2% EAFD (color code S1002Y), the predominant color is yellow with 10% darkness and 2% saturation. For both glazes with 4% EAFD (color code S1505Y), the predominant color is yellow with 15% darkness and 5% saturation. For both glazes with 6% EAFD (color code S1510G90Y), the predominant colors are green (10%) and yellow (90%) with 15% darkness and 10% saturation. Different colors of the glazes of BGS and CBT can be observed for the cases with 8% EAFD. Whereas the BGS-8 glaze (color code S2020Y) is predominantly yellow with 20% darkness and 20% saturation, the CBT-8 glaze (color code S2010Y10R) is predominantly red (10%) and yellow (90%) with 20% darkness and 10% saturation.

Table 4 – Results of colorimetric analysis of BGS and CBT samples according to CIE system.

<table>
<thead>
<tr>
<th>BGS and CBT samples</th>
<th>Samples</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>Color code (NCS)</th>
</tr>
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<tr>
<td>BGS samples</td>
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<td>−0.74</td>
<td>5.27</td>
<td>S1002Y</td>
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<td></td>
<td>BGS-4</td>
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<td>−0.78</td>
<td>10.12</td>
<td>S1505Y</td>
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<tr>
<td></td>
<td>BGS-6</td>
<td>82.60</td>
<td>−1.60</td>
<td>15.89</td>
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<td></td>
<td>BGS-8</td>
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<td>25.44</td>
<td>S2020Y</td>
</tr>
<tr>
<td>CBT samples</td>
<td>CBT-2</td>
<td>87.35</td>
<td>−0.74</td>
<td>5.27</td>
<td>S1002Y</td>
</tr>
<tr>
<td></td>
<td>CBT-4</td>
<td>83.86</td>
<td>−0.78</td>
<td>10.12</td>
<td>S1505Y</td>
</tr>
<tr>
<td></td>
<td>CBT-6</td>
<td>82.60</td>
<td>−1.60</td>
<td>15.89</td>
<td>S1510G90Y</td>
</tr>
<tr>
<td></td>
<td>CBT-8</td>
<td>82.23</td>
<td>1.13</td>
<td>17.32</td>
<td>S2010Y10R</td>
</tr>
</tbody>
</table>

Fig. 9 – Colors of BGS samples: (a) BGS-2, (b) BGS-4, (c) BGS-6, (d) BGS-8.

4. Conclusions

The EAFD is an industrial waste resulting from steelmaking processes and is hazardous according to the Brazilian standard ABNT NBR 10004/2004 and European Waste Catalogue (EWC 2002) owing to the presence of heavy metals such as chromium, lead, and cadmium. However, EAFD comprises
other compounds such as zinc oxide and iron oxide, which can be reused. In this study, the EAFD exhibited high amounts of iron oxide (44.60%) and zinc oxide (26.24%) with its main crystalline phases being zinctite, magnetite, and other phases with spinel structures. The EAFD exhibits great potential to be reused as raw material in the glaze production because of the included magnetite—a well-known pigment. The investigated EAFD exhibited a low average particle size (0.770 µm) and thermal stability. Ceramic tiles covered with the EAFD-containing glazes (BGS and CBT) can be applied in residential environments owing to their PEI 3 rating. The reuse of the co-product as glaze for ceramic tiles is a viable and sustainable alternative. Further, the method helps the steel industry to reduce expenses related to the disposal of this dust type, and the resulting glazes could be an economically interesting alternative for the ceramic industry.

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References


Fig. 10 – Colors of CBT samples: (a) CBT-2, (b) CBT-4, (c) CBT-6, (d) CBT-8.


