Characterisation and leaching behaviour of granulated iron silicate slag constituents

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ABSTRACT
Due to increased copper production and the associated environmental consequences, copper production processes need to be improved, considering the impact of their byproducts, among others slag. This study investigated the leaching of individual constituents of iron silicate slag from a copper smelter. This was done by characterising granulated samples of its constituents—glass, matte, speiss—to determine their leaching contribution. It was observed that leaching in distilled and deionised water without pH regulation achieved various natural pH for the constituents. At natural pH, glass (Cu, Zn) and speiss (Ni, Sb) contributed to leaching. Static pH titrations showed the increased leaching of Zn, Cu, Ni, As, and Sb with decreasing pH. The results showed that, an iron silicate slag consisting of glass, matte and speiss, contributes to leaching as follows: matte – Cu and Ni, speiss – Cu, Ni, As, and Sb. Zn leaching is similar among the constituents.

1. Introduction
In 2019, the global copper production through the pyrometallurgical route reached approximately 20 Mt [1]. For each 1 t of copper, the pyrometallurgical route generates approximately 2.2 t of slag [2]. Slag is usually treated to recover copper using different slag cleaning processes, such as settling, and in some cases slag fuming [3,4], to remove entrained copper sulﬁde (matte) and copper metalloid (speiss). Fuming processes treat the molten slag by blowing a pulverised reductant, usually coal, and air into the furnace to reduce the dissolved metal oxides to their metal phases [5–7]. In addition to the removal of copper, this process allows the recovery of zinc and the removal of lead and cadmium from the slag. The fumed molten slag then undergoes gravitational settling to separate sulﬁdes and metal (loid)s into a matte and speiss layer. The molten slag, from which copper has been removed, is solidiﬁed by air cooling or granulation. With granulation, the slag becomes amorphous to various degrees depending on its composition and granulation method. Slag treatments cannot completely remove all matte and speiss; some of them remain trapped in the produced slag as both entrained and dissolved copper compounds. Therefore, the produced copper slags still contain varying amounts of matte and speiss. Depending on the copper smelting and specific slag cleaning processes, the copper content of the final slag varies from 0.2 to 5 wt. % [2,8–10], consisting of Cu and typical Cu-carrying compounds – Cu5FeS4 and Cu2S [11–13]. Some studies showed that copper can also be dissolved as Cu2O in the slag [5,14]. The final granulated slag from the slag
treatment can either be used in different external applications, such as in sandblasting and road sub-base construction, or discarded to a landfill. For all end use applications (slags), their environmental impacts should be determined. It is common for potential environmental consequences of usage to be determined, usually by applying leaching tests. Particularly, in Europe, slags are classified for leaching with leaching limits of environmental critical elements using the EN 12457-2 protocol [15].

There are several studies on the overall leaching behaviour of copper slag [16–19]. These studies often have an environmental geochemical approach without the consideration of the slag processing at copper smelters. Typical elements leached from iron silicate slags are Zn, Cu, and Ni [20]. In some cases, the leaching of As, Co, Sb, and Cd can be an issue [18,20] depending on the raw materials used. The pH value for the leaching tests of copper slag is usually in the range of 7–10, in which the solubility of metal ions is at its lowest. Moreover, available metal hydroxides and sulfides easily precipitate in this pH range [11,21,22]. Therefore, leaching studies at acidic pH values should also be conducted to simulate acidification by external sources or sulfide oxidation. Acidic test conditions substantially increase the leaching values of metals and sulfides [11,21,23,24]. Lidelöw et al. conducted a long-term field test to analyse water from lysimeters collected after passing different residue materials in a test bed. Their study showed the occurrence of leaching from iron silicate slag over a limited period, peaking after 2–4 years, and thereafter decreasing over time. Further, the study showed that the pH of leachates from the test bed varied between 6.3 and 7.8 with an average of 6.9 [20]. Piatak et al. indicated that the leaching of trace elements (As, Co, Cu, and Pb) is from glass, sulfides, and metal(loids); however, the leaching behaviour of these specific hosts was not determined [12]. Furthermore, even with the acknowledgement of the presence of various hosts, and their importance in steelmaking slags [25,26], there are limited experiments and studies on their leaching behaviour in copper slags. Particularly, there is yet to be a study on the leaching of iron silicate slags focused on the contribution of the different hosts, which are hereafter referred to as slag constituents (also known as slag phases or slag minerals). Leaching from slags is an issue regarding its end use applications. Improved knowledge about the slag leaching mechanism and its cause gives valuable information about leaching minimisation. This knowledge is important for copper smelters to further improve slag treatment processes as settling, leaching, and slag chemistry modifications to enhance the environmental stability of slag in end use applications. Further, it will open new application areas and a more sustainable use of materials.

Therefore, this study aims to determine the contribution and leaching mechanism of the separate slag constituents of a water granulated iron silicate slag – glass (amorphous oxide), matte (copper sulfide), and speiss (metalloid). The granulated slag constituents are characterised and the leaching of their main elements (Cu, Fe, Ni, As, Sb, and Zn) are examined at natural and acidic pH.

2. Materials and methods

2.1. Preparation of the materials

The materials for this study – separate samples of iron silicate slag, matte, and speiss – were obtained from the materials tapped from the electrical settling furnace (ESF) at Boliden Rönnskär smelter, Sweden. At the smelter, the copper smelting slag underwent a zinc-fuming process followed by settling in the ESF. The settled slag is water granulated when tapped from the furnace. During the process, matte and speiss inclusions are settled at the bottom of the furnace and tapped into a slag ladle where they are further divided into two separate layers of matte and speiss by their density differences [6,7]. The granulated iron silicate slag was dewatered at the smelter slag storage and the slag was collected and stored as received in a steel barrel with drilled holes in the bottom for further dewatering prior to the study. The matte and speiss layers from the slag ladle were stored at the smelter site to cool down and fractions of matte and speiss were collected for the study. The matte and speiss samples were stored as received prior to the study. Figure 1 shows the preparation procedure of the samples. A sub-sample of the received iron silicate slag was dried and homogenised by grinding (<1 mm) in a rod mill with iron rods. The magnetic particles (grinding media) were...
removed by magnetic separation using a SALA low-intensity magnetic separator (Mortsell separator). The subsample of the ground slag sample was remelted to settle and separate Cu-containing inclusions in a Nernst-Tammann carbon-resistance furnace supplied by Ruhstrat K.G. The remelting was executed at 1250°C for 120 min at iron saturation using crucibles made of ARMCOPure iron © under an argon atmosphere. The shorter smelting time for the matte and speiss samples minimised sulfur evaporation and metal oxidation. Each type of molten samples was water granulated from the crucibles directly after the melting period with a constant water flow rate of 1.1 L/s. The laboratory granulation unit and process are described elsewhere by Feng et al. [27]. All the samples were collected, dried, and split separately before characterisation and leaching analysis.

2.2. Granulation of the materials

The prepared glass, matte, and speiss subsamples were separately melted and water-granulated in batches using a muffle furnace for 30, 10, and 10 min, respectively, at 1250°C in crucibles made of ARMCOPure iron © under air atmosphere. The shorter smelting time for the matte and speiss samples minimised sulfur evaporation and metal oxidation. Each type of molten samples was water granulated from the crucibles directly after the melting period with a constant water flow rate of 1.1 L/s. The laboratory granulation unit and process are described elsewhere by Feng et al. [27]. All the samples were collected, dried, and split separately before characterisation and leaching analysis.

2.3. Characterisation methods

The as-received iron silicate slag, and subsamples of glass, matte, and speiss were analysed for their chemical composition by the ALS Scandinavia AB Laboratory, Sweden, using lithium metaborate digestion (ASTM D3682:2013 and ASTM D4503:2008), HNO3/HCl/HF digestion (SS EN 13656:2003), and inductively coupled plasma sector field mass spectrometry (ICP-SFMS) (SS EN ISO 17294-2:2016 and EPA-method 200.8:1994). The mineralogy of the carbon-coated and -polished epoxy moulds of the samples was analysed by scanning electron microscopy (SEM) on a Zeiss Gemini Merlin instrument equipped with an Oxford Instruments energy dispersive spectroscopy (EDS) detector at an accelerating voltage of 20 keV and emission current of 1.0 nA. The semi-quantitative and qualitative measurements of the elements in the samples were provided by point analysis. Powder X-ray diffraction (XRD) was carried out with a PANalytical Empyrean X-ray diffractometer with a copper Ka radiation source at a voltage of 45 mV and current of 40 mA, and a monochromator. The measurements were conducted over a 2θ range of 25–90° with a step size of 0.026°. The received XRD patterns were examined with the Highscore Plus software and Crystallography Open Database [28] to determine the crystalline compounds in each sample. Specific surface area analysis was conducted using the Brunauer–Emmett–Teller (BET) approach and a Micromeritics FlowSorb II 2300 on the granulated samples to determine the specific surface areas (m²/g) of the sample fractions sized 0.30–0.60 mm.

2.4. Leaching of the materials

One-stage batch leaching test according to EN 12457-2 standard (liquid/solid 10 L/kg) was used in this study to compare the leachability of the different samples. The leaching test followed the standard protocol except for the use of 25 g solids with a size fraction of 0.30–0.60 mm for each sample type to reduce the variation in the particle size and surface area between the samples. The eluates from the leaching test were filtered, acidified with 1 vol.% of 68% HNO3, supplied by VWR Chemicals, and analysed for Al, As, Ba, Ca, Cr, Cu, Fe, K, Mg, Mo, Na, Ni, S, Sb, Sn, Si, P, Pb, Zn, and Ti by ICP optical emission spectrometry (ICP-OES) on a Thermo Scientific iCapTM 7200 duo ICP-OES at the Luleå University of Technology using multielemental standards. The elemental concentrations per amount of solid matter in the eluates (mg/kg) are presented as the average value of the two or three samples with the associated standard deviations.

Table 1. Chemical compositions (wt.%) of the granulated glass, matte, speiss, and iron silicate slag samples.

| Element | Glass | Matte | Speiss | Iron silicate slag |
|---------|-------|-------|--------|-------------------|
| Si      | 16.5  | 10.1  | 0.7    | 16.3              |
| Al      | 2.48  | 0.02  | 0.02   | 2.06              |
| Ca      | 2.74  | <0.06 | <0.05  | 2.21              |
| Fe      | 35.0  | 8.66  | 19.5   | 36.0              |
| K       | 0.44  | <0.02 | 0.02   | 0.43              |
| Mg      | 0.90  | 0.03  | 0.02   | 0.74              |
| Mn      | 0.38  | 0.01  | 0.01   | 0.34              |
| Na      | 0.47  | <0.03 | <0.02  | 0.36              |
| As      | 0.002 | 1.06  | 7.83   | 0.018             |
| Ba      | 0.24  | 0.0014| 0.0006 | 0.24              |
| Cd      | 0.00007| 0.00001| 0.00002| 0.00008          |
| Co      | 0.03  | 0.08  | 0.09   | 0.05              |
| Cr      | 0.19  | <0.001| 0.002  | 0.17              |
| Cu      | 0.30  | 66.5  | 46.7   | 0.78              |
| Mo      | 0.081 | 0.003 | 0.003  | 0.117             |
| Ni      | 0.01  | 1.80  | 6.74   | 0.04              |
| Pb      | 0.02  | 0.06  | 0.21   | 0.03              |
| Rb      | 0.38  | 19.1  | 8.81   | 0.54              |
| Sb      | 0.003 | 0.94  | 6.60   | 0.025             |
| Sn      | 0.08  | 0.17  | 2.77   | 0.17              |
| Zn      | 1.05  | 0.20  | 0.06   | 1.32              |
| O⁺      | 38.3  | 2.94  | 8.47   | 37.8              |

*Summarized stoichiometric oxygen based on Si, Al, Ca, Fe⁺⁺⁺, K, Mg, Mn, Na, P, and Ti in slag samples.
2.5. Static pH titration of the materials

The static pH titrations on the granulated glass, matte, and speiss samples were conducted for the particle size fraction of 0.15–0.30 mm. The titrations were performed at pH 3, 5, 7, and natural pH (‘N’) using 0.025–0.5 M HNO₃ acid with an initial amount of 5.0 g sample and 50.0 mL milli-Q water. All titrations were executed in a stirred reactor at 25°C for 24 h in an open system with the surrounding air and a stirring rate of 300 rpm using a magnetic stirrer. Like the eluates from the leached samples, the liquid phase from the titrations was analysed with ICP-OES. The results for Cu, Fe, Ni, Zn, As, and Sb are presented as the elemental concentration per amount of solid matter (mg/kg).

3. Results and discussion

3.1. Characterisation of the slag constituents

Table 1 shows the results from the chemical analyses of the as-received iron silicate slag and granulated glass, matte, and speiss samples. The main elements in the iron silicate slag were Fe, Si, and O; other elements with contents above 1 wt.% are Ca, Al, and Zn. Similarly, the granulated glass sample contained Fe, Si, O, Ca, Al, Zn, Mg, and Mn. The glass sample contained 0.30 wt.% Cu and 1.05 wt.% Zn, which are reduced by approximately 60 and 20 wt.%, respectively, due to the remelting and granulation operations. The remelting treatment also reduced the amounts of S, Ni, As, Sb, and Sn in the glass sample compared with the results of the chemical analysis of the iron silicate slag, as shown in Table 1. Further, the main elements in the spherical granulated matte sample in descending order are Cu, S, Fe, and Ni. The main elements in the speiss sample in descending order are Cu, Fe, As, Sb, and Sn.

The SEM-EDS analysis shown in Figure 2 shows the presence of the three slag constituents in the iron silicate slag sample (spinel is included in the glass). The matte and speiss constituents are both found as inclusions in clusters and separated in the iron silicate slag matrix. The glass sample is a mixture of spherical particles with a homogeneous composition of mainly Fe, Si, and O, as shown in Figure 4(a,b). However, according to the SEM-EDS analysis, traces of entrained droplets of copper sulfides (Cu, Fe, S), copper metalloids (Cu, Ni, As, Sb, Sn), and iron oxides (Fe, Cr, Zn, O) remain in the glass sample. In the matte sample, the SEM image and EDS profile in Figure 4(c,d) show the main phase of Fe-containing copper sulfide (Cu, Fe, S). Further, the SEM images show internal crack formations in the matte granules. Minor inclusions of copper metalloids are present as entrained Cu droplets, which are associated with As, Sb, and Sn, according to the EDS analysis (not shown in figures). The SEM-EDS analysis in Figure 4(e,f) shows that the speiss granules mainly contain Cu (with varying content) and minor amounts of Fe, Ni, As, Sb, and Sn. Moreover, according to SEM-EDS analysis (not shown in figures), the speiss sample contains minor inclusions of Cu–S, Fe–O, Fe, and Pb.

The XRD analysis shown in Figure 3(a) indicates that the glass sample is amorphous due to the ‘halo’ between 2θ values of 25° and 38° and the lack of characteristic peaks of Fe–Si–O compounds. In the matte sample, the XRD pattern shows the presence of Cu₅FeS₄, Cu₂S, and metallic Cu crystalline compounds. The XRD pattern of the speiss sample shows the peaks of metallic Cu, copper metalloids (Cu₀.₉₉₅Sb₀.₀₅), Fe₃O₄, FeO, and metallic Fe. The identified iron-containing compounds originated both from the speiss itself and the Fe crucible.

The particle size distributions of the granulated glass, matte, and speiss samples were all in the range 0–2 mm with d₈₀ values of 1.08, 1.54, and 1.43 mm, respectively. The BET surface areas of the 0.30–0.60 mm size fraction of the glass, matte, and speiss samples used in the leaching tests were 0.05, 0.26, and 0.03 m²/g, respectively.

3.1.1. Elemental distribution in the glass, matte, and speiss samples

The result of the chemical analysis (Table 1) shows that most Zn is in the glass sample and the SEM-EDS analysis (Figure 4(b,d)) further confirms its main distribution in the glass matrix, which is in accordance with earlier studies [18,29]. Table 1 also shows that Cu, S, As, Ni, Sb, and Sn are the main elements in the matte (Cu, S)
and speiss (Cu, As, Sb, Ni, Sn) samples, the results are in coherence with previous studies and are commonly found in copper slags [11–13]. According to the XRD analysis, these elements are mainly associated with the sulfide and metalloid phases, as shown in Figure 3(b,c). Furthermore, the distribution of Cu in the matte sample agrees with the Cu-containing compounds found in the slags from previous studies [11,12].

3.2. Leaching of the elements from slag constituents

Table 2 presents the received pH-values, conductivity, and leaching values of the elements in the 0.3–0.6 mm size fraction of the granulated glass, matte, and speiss samples according to the modified version of EN 12457-2. These leaching tests in distilled and deionised water without pH regulation resulted in various natural pH for the constituents. From the glass sample, Cu, Zn, and Mo have the highest leaching values among the tabulated elements at the received pH 8.4 (Table 2). S and Ni associated with the matte sample exhibited low leaching values at its received pH 9.3. Moreover, the leaching values of Cu, Fe, As, Sb, Sn, and Zn were all below the detection limits for the matte sample. The speiss sample showed leaching of Sb, Ni, and Cu, in decreasing order, at its received pH 7.8. The leaching values of Fe, As, and Sn were below their detection limits.

Figure 4. (a, c, e) Scanning electron microscopy images and (b, d, f) energy dispersive spectroscopy profiles of the granulated glass, matte, and speiss samples.
3.2.1. Leaching contribution from the slag constituents

The investigated glass, matte, and speiss samples demonstrated low leachability, as indicated by their conductivity with a maximum of 11.4 µS/cm obtained for the glass sample. The conductivity obtained from the samples are low compared with most natural hydrological compartments [30], which indicates low total dissolved ion concentrations. The glass sample showed the highest leaching contribution of Cu and Zn, according to Table 2, and thereby contributes to their leaching although their contents were reduced by remelting and separation of Cu inclusions and Zn vaporisation. Zn leaching is expected to occur since the glass is the main Zn-carrier (ZnO), and also because Zn²⁺ is formed in a Zn-O-H system at more acidic pH [31]. The Cu leaching is explained by the leaching of the remaining Cu (metallic) or CuOₓ (dissolved) in the glass. However, it is not solely affected by pH but also the Cu source, since the speiss sample, with higher Cu content (approximately 47 wt.% Cu (metallic/metalloid)), shows lower Cu leaching although it has lower pH (0.6 units lower). The matte sample shows minor contribution at pH 9.3, which is in accordance with the low solubility of metal sulfides and hydroxides as shown by Lewis in the pH-range 8–10 [22]. Therefore, the Cu leaching caused by sulfides is minimal. Hence, CuOₓ (if present) likely contributed to the Cu leaching from the glass in a similar manner as the ZnO contributed to Zn leaching [31,32]. The speiss sample exhibited the lowest conductivity but the highest leaching contribution of Ni and Sb. For the matte sample, the leaching of Cu, Fe, Ni, Sb, and Zn was generally lower than those of the glass and speiss samples. The leaching of As is below the detection limit for all the samples as shown in Table 2.

3.3. Static pH titration

The static pH titration method shows the leaching of Cu, Fe, Ni, Zn, As, and Sb from the sample glass, matte, and speiss at pH 3, 5, 7, and natural pH as shown in Figure 5(a–f). The results show a pH-dependent leaching of all elements, which are in accordance with earlier studies on copper slag leaching [21,33]. The leaching from the matte and speiss samples follows the same general leaching trends as for the glass. The leaching values of Cu, Fe, Ni, As, and Sb (matte and speiss) increase with the decrease in the pH from 7 to 3 for all samples. Cu, Ni, As, and Sb leaching values are consistently higher for the matte and speiss samples than those for the glass sample. Further, comparing the Fe (glass main element) and Cu (matte and speiss main element) leaching at pH 5 (Figure 5(a,b)), the result indicates that the glass, matte, and speiss matrixes are not dissolved to equal extents. Therefore, with the decrease in pH, matte and speiss samples dissolve to a higher degree than the glass matrix. The higher leachability of Cu compared with Fe in the constituents is due to the predominant state (Cu²⁺, FeO) of the elements at the studied pH and the oxidation conditions for the Cu-O-H and Fe-O-H systems, respectively [32].

Iron silicate slag with constituents of glass, matte and speiss shows leaching contribution of Cu, Ni, As, and Sb in the pH range of 3–7 at oxidation conditions, in which the overall leaching of Cu is mainly controlled by the matte and the leaching of Ni comes from both the matte and speiss. The leaching of As and Sb is controlled by the speiss at pH 7 and 5 and is similar for the speiss.
and matte samples at pH 3, probably due to the higher dissolution of inclusions in the matte sample.

3.4. Observed interactions among slag constituents

The sample surface area is an important parameter which influences leaching from different materials. The BET surface areas of the glass, matte, and speiss samples, with size fractions of 0.3–0.6 mm, are in the ratio 1:5:0.5. Considering the surface areas of the samples, the leaching contribution from matte and speiss change relative to the glass sample, as illustrated in Figure 6 for Cu, and Zn. The leaching values, LV (mg/kg and mg/dm²), are compared to the highest leaching value, LV_{max}, for each element and unit (kg and dm²), respectively, using the formula

\[
\text{Leaching index} = \frac{\text{LV}}{\text{LV}_{\text{max}}} \times 100.
\]

Despite the surface area effect, the leaching of Cu, Ni, As, and Sb originate from the matte and speiss samples; however, it is slightly more inclined to the speiss sample. Therefore, the main cause of the leaching (Cu, Ni, As, Sb) seems to be the Cu-metalloid), which is identified both in the matte and speiss sample by XRD, which

Figure 5. Elemental release, log[mg/kg], of (a) Cu, (b) Fe, (c) Ni, (d) Zn, (e) As, and (f) Sb by pH titrations at pH 3, 5, 7, and natural pH ‘N’, where N is 7.9, 8.4, and 7.9 for glass, matte and speiss samples, respectively.
preferably dissolves under the acidic and oxidation conditions at static pH titrations [32]. This finding indicates the need to minimise the amount of primary speiss and secondary matte to minimise the overall leaching of Cu, Ni, As, and Sb in iron silicate slags. Similar leaching values for Zn indicates that Zn leaching mainly originates from the glass part, which also is shown in Table 2 and Figure 6, when the surface area is taken into consideration. The Zn leaching is earlier reported to originate from the slag matrix for the studied slag type [18].

In an iron silicate slag with the slag constituents of glass, matte, and speiss, glass is the dominant component, while both matte and speiss only takes up <2 wt.% together (Table 1). This corresponds to the findings in a study by Wang et al., which concluded that the total content of Cu-bearing compounds, in a similar slag, are approximately 0.65 vol %. Therefore, it is reasonable to assume that the dominant glass part sets the pH of water in contact with the slag. Lidelöw et al. found that the pH of leaching water from an industrial slag testbed measured an average pH of 6.9 in the range 6.3–7.8 [20]. The leaching contribution from the matte and speiss granules (in this study) is more severe for Cu and Ni at pH 7 than at their natural pH 8.4 and 7.9, respectively, based on the static pH titration (Figure 5(a,c)). This indicates that the leaching from the matte and speiss samples differ when they are part of an iron silicate slag. Furthermore, the leaching of Cu and Ni from matte and speiss impacts the overall leaching at pH 7 and below. Moreover, the leaching of As and Sb from matte and speiss affects the overall leaching of the iron silicate slag at the entire pH range. Thus, matte and speiss in slag should be minimised to avoid the leaching of Cu and Ni, and particularly As and Sb at pH 3–7.

In addition, the characterisation of the iron silicate slag constituents shows that the matte and speiss are both located as liberated droplets or as matte droplets with a core of speiss, as shown in Figure 2. Therefore, the leachability of Cu, Ni, As, and Sb should follow the same trends, which also partly occur for both the matte and the speiss samples in this study, as shown in Figure 5(a,c,e,f). Hence, the elemental leaching values differ depending on the surface availability of the matte and speiss constituents in iron silicate slag.

Another aspect that also affects the leaching contribution is the distribution of Cu in the glass as either inclusions or dissolved CuOx. The static pH titration results for the natural pH 'N' (Figure 5(a)) shows that the Cu leaching contribution from glass is limited compared with the matte and speiss due to the low dissolution of the glass matrix, even if it has the highest leaching contribution using the EN12457-2 tests (Table 2). This further proves that the matte and speiss leaching contributions cannot be neglected (if present) in iron silicate slags at the studied conditions.

4. Conclusions
The results from this study provide new information about the source of the leaching from iron silicate slag constituents: glass, matte, and speiss specimens. The following conclusions were drawn:

- The studied slag constituents, namely granulated glass, matte, and speiss, exhibit natural leaching
The magnitude of the leaching contribution from the matte and speiss matrices (Cu-rich silicate) dissolves more extensively than the glass matrix (iron silicate) at the investigated conditions and pH.

The minimisation of matte and speiss in an iron silicate slag is a possible method that can be employed by copper smelters to produce more environmentally stable slag end use products.

Acknowledgements

The authors of this paper are thankful for all support from co-workers at the Luleå University of Technology and partners at the Boliden Rönnskär smelter.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was conducted within the strategic innovation program STRIM, a joint investment in strategic innovation areas by Vinnova, Formas and the Swedish Energy Agency and within Center of Advanced Mining and Metallurgy (CAME) at Luleå University of Technology.

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References

[1] International Copper Study Group. The World Copper Factbook 2020. 2020.
[2] Gorai B, Jana RK, Premchand M. Characteristics and utilisation of copper slag – a review. Resour Conserv Recycl. 2003;39:299–313. doi:10.1016/S0921-3449(02)00171-4.
[3] Schlesinger ME, King MJ, Sole KC, et al. Matte smelting fundamentals. In: Schlesinger ME, King MJ, Sole KC, Davenport WG, editors. Extractive metallurgy of copper. Oxford: Elsevier; 2011. p. 73–88.
[4] Mariscal L, Herrera E. ISASMELT TM slag chemistry and copper losses in the rotary holding furnaces slag at Ilo smelter. In: Sanchez M, editor. 8th international conference on molten slags, fluxes & salts. Santiago; 2009. p. 1241–1250.
[5] Schlesinger ME, King MJ, Sole KC, et al. Copper loss in slag. In: Schlesinger ME, King MJ, Sole KC, Davenport WG, editors. Extractive metallurgy of copper. Oxford: Elsevier; 2011. p. 191–203.
[6] Lotfian S, Vikström T, Lennartsson A, et al. Plastic-containing materials as alternative reductants for base metal production. Can Metall Q. 2019;58:164–176. doi:10.1080/00084433.2018.1532951.
[7] Borell M. Slag—a resource in the sustainable society. In: Securing the future; proceedings of the international conference on mining, environment, metals, energy recovery. Skellefteå; 2005. p. 130–138.
[8] Coursol P, Valencia NC, Mackey P, et al. Minimization of copper losses in copper smelting slag during electric furnace treatment. JOM. 2012;64:1305–1313. doi:10.1007/s11837-012-0454-6.
[9] Kim HG, Sohn HY. Effects of CaO, Al2O3, and MgO additions on the copper solubility, ferric/ferrous ratio, and minor-element behavior of iron-silicate slags. Metall Mater Trans B Process Metall Mater Process Sci. 1998;29:583–590. doi:10.1007/s11663-998-0093-z.
[10] Sridhar R, Toguri JM, Simeonov S. Copper losses and thermodynamic considerations in copper smelting. Metall Mater Trans B Process Metall Mater Process Sci. 1997;28:191–200. doi:10.1007/s11663-997-0084-5.
[11] Piatak NM, Seal RR, Hammarstrom JM. Mineralogical and geochemical controls on the release of trace elements from slag produced by base- and precious-metal smelting at abandoned mine sites. Appl Geochem. 2004;19:1039–1064. doi:10.1016/j.apgeochem.2004.01.005.
[12] Takebe H, Tomita S, Saitoh A, et al. Effect of crystallization on microstructure and elution properties in copper slag. J Sustain Metall. 2017;3:543–550. doi:10.1007/s40831-017-0130-8.
[13] Fagerlund KO, Jalkanen H. Microscale simulation of settler processes in copper matte smelting. Metall Mater Trans B Process Metall Mater Process Sci. 2000;31:439–451. doi:10.1007/s11663-000-0150-8.
[14] Alter H. The composition and environmental hazard of copper slags in the context of the Basel convention.
[17] Dung TTT, Cappuyns V, Swennen R, et al. Leachability of arsenic and heavy metals from blasted copper slag and contamination of marine sediment and soil in Ninh Hoa district, south central of Vietnam. Appl Geochem. 2014;44:80–92. doi:10.1016/j.apgeochem.2013.07.021.

[18] Piatak NM, Parsons MB, Seal RR. Characteristics and environmental aspects of slag: a review. Appl Geochem. 2015;57:236–266. doi:10.1016/j.apgeochem.2014.04.009.

[19] Tossavainen M, Forssberg E. Leaching behaviour of rock material and slag used in road construction – a mineralogical interpretation. Steel Res. 2000;71:442–448. doi:10.1002/srin.200005713.

[20] Lidelöw S, Mácsik J, Carabante I, et al. Leaching behaviour of copper slag, construction and demolition waste and crushed rock used in a full-scale road construction. J Environ Manage. 2017;204:695–703. doi:10.1016/j.jenvman.2017.09.032.

[21] Jarošíková A, Ettler V, Mihaljevič M, et al. The pH-dependent leaching behavior of slags from various stages of a copper smelting process: environmental implications. J Environ Manage. 2017;187:178–186. doi:10.1016/j.jenvman.2016.11.037.

[22] Lewis AE. Review of metal sulphide precipitation. Hydrometall. 2010;104:222–234. doi:10.1016/j.hydromet.2010.06.010.

[23] Yang Z, Rui-Lin M, Wang-Dong N, et al. Selective leaching of base metals from copper smelter slag. Hydrometall. 2010;103:25–29. doi:10.1016/j.hydromet.2010.02.009.

[24] Perederiy I, Papangelakis VG. Why amorphous FeO-SiO2 slags do not acid-leach at high temperatures. J Hazard Mater. 2017;321:737–744. doi:10.1016/j.jhazmat.2016.09.055.

[25] Engström F, Larsson ML, Samuelsson C, et al. Leaching behavior of aged steel slags. Steel Res Int. 2014;85:607–615. doi:10.1002/srin.201300119.

[26] Engström F, Adolfsson D, Samuelsson C, et al. A study of the solubility of pure slag minerals. Miner Eng. 2013;41:46–52. doi:10.1016/j.mineng.2012.10.004.

[27] Feng Y, Yang Q, Chen Q, et al. Characterization and evaluation of the pozzolanic activity of granulated copper slag modified with CaO. J Clean Prod. 2019;232:1112–1120. doi:10.1016/j.jclepro.2019.06.062.

[28] Gražulis S, Daškevič A, Merkys A, et al. Crystallography Open Database (COD): an open-access collection of crystal structures and platform for world-wide collaboration. Nucleic Acids Res. 2012;40:D420–D427. doi:10.1093/nar/gkr900.

[29] Wang Z, Zhao Z, Zhang L, et al. Formation mechanism of zinc-doped fayalite (Fe2-xZnxSiO4) slag during copper smelting. J Hazard Mater. 2019;364:488–498. doi:10.1016/j.jhazmat.2018.10.071.

[30] Federation WE, Association APH. Standard methods for the examination of water and wastewater. Am Public Heal Assoc Washington, DC; 2005.

[31] Song S, Sun W, Wang L, et al. Recovery of cobalt and zinc from the leaching solution of zinc smelting slag. J Environ Chem Eng. 2019;7:102777. doi:10.1016/j.jece.2018.11.022.

[32] Huang HH. The Eh-pH diagram and its advances. Metals (Basel). 2016;6:23. doi:10.3390/met6010023.

[33] Shanmuganathan P, Laksh mipathiraj P, Srikanth S, et al. Toxicity characterization and long-term stability studies on copper slag from the ISASMELT process. Resour Conserv Recycl. 2008;52:601–611. doi:10.1016/j.resconrec.2007.08.001.