

METALLURGICAL VALORIZATION OF STEEL SLAG VIA VIBROFLUID MAGNETIC SEPARATION: TOWARD NEAR-ZERO WASTE UTILIZATION

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Abstract

This study investigates the potential utilization of converter steel slag after vibrofluid magnetic separation (VMS) for the preparation of ceramic glazes. Converter slag (CS) represents a significant by-product of steel production, and its effective recycling is essential for sustainable resource management and circular economy strategies. A slag sample obtained from steel production was classified into three particle-size fractions (<0.2 mm, 0.2-0.6 mm and >0.6 mm) and subsequently subjected to dry vibrofluid magnetic separation. The resulting magnetic (MF) and non-magnetic (NF) fractions were characterized using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The results confirmed significant redistribution of iron-bearing phases into magnetic fractions, where Fe_2O_3 concentrations increased to approximately 37-40 wt. %, while CaO and silicate phases were enriched in the non-magnetic fractions. Both fractions were subsequently evaluated as raw materials for ceramic glaze preparation in combination with waste glass. A total of 24 glaze formulations were prepared and fired at 1,060 °C and 1,160 °C, and their colour properties were assessed using the CIE Lab colour system. The results showed that magnetic fractions generally produced darker and more reddish-brown glazes due to higher iron content, whereas non-magnetic fractions yielded brighter tones. Appropriate slag-to-glass ratios and firing temperatures resulted in stable glaze surfaces. These findings demonstrate that both magnetic and non-magnetic slag fractions can serve as valuable secondary raw materials for ceramic glaze production, supporting comprehensive utilization of steel slag and contributing to sustainable waste management.

Keywords: Converter slag, vibrofluid magnetic separation, waste ceramic, glazes, secondary raw materials

1. INTRODUCTION

Blast furnace slag (BFS) is widely used as a secondary raw material in the cement industry, particularly in the production of hydraulic cement binders. In contrast, a large portion of converter slag (CS) is still disposed of in controlled landfills, despite its potential for reuse. BOF slag has been utilized in several applications, including construction materials, road pavements, agricultural fertilizers, soil conditioners, and as a raw material for the production of glass and glass-ceramics [1]. However, its broader utilization is limited mainly by the high CaO content (25-55 wt. %), particularly the presence of free lime and free magnesia, which can hydrate and cause volumetric expansion and swelling [2,3]. CS also contains a relatively high amount of iron (14-30 wt. %), which makes iron recovery an important processing step. Conventional methods such as crushing, grinding, screening, and magnetic separation can achieve iron recovery very high efficiencies [4,5].

Magnetic separation is widely applied in the processing of industrial wastes due to its ability to selectively recover valuable components while supporting sustainable resource management. Effective conversion of waste into industrial raw materials strongly depends on efficient separation techniques [6,7]. Owing to its low operational cost, environmental friendliness, high efficiency, and large processing capacity, magnetic separation is considered a promising method for converting waste materials into valuable commodities.

Building upon these considerations, the present study investigates the potential utilization of both magnetic and non-magnetic concentrates obtained from converter slag (CS) for the preparation of ceramic glazes. Magnetic separation enables the recovery of iron-rich fractions that can be potentially returned to metallurgical processes, while the remaining non-magnetic material may serve as a secondary raw resource for value-added products. By experimentally evaluating both fractions as functional precursors for glaze formulations, this study aims to promote a more comprehensive utilization of converter slag and reduce the amount of residual waste. In this way, the proposed approach contributes to circular economy strategies focused on resource efficiency and sustainable materials development.

2. EXPERIMENTAL METHODS AND MATERIAL CHARACTERISATION

Converter slag sample obtained from steel production in Třinecké železářny a.s., (Czech Republic), was used as the experimental material. The waste glass (labelled as WG) sample was obtained after the demolition of the Werk Arena station in Třinec (Czech Republic). Prior to XRF and XRD analysis, the samples were dried at 105 °C for 24 h to achieve constant weight. After drying, the materials were cooled in a desiccator to prevent moisture uptake and subsequently weighed. Before magnetic separation, the CS was sieved into three particle-size fractions (< 0.2 mm, 0.2 - 0.6 mm and > 0.6 mm), which were subsequently subjected to dry magnetic separation in a vibrofluid state (VMS - vibrofluid magnetic separation). The method promotes the formation of a “granular gas” state, minimizing particle agglomeration and enabling selective separation. All magnetic (MF) and non-magnetic (NF) size fractions and WG were pulverized by using a vibratory disc mill for 2 min and sieved below 0.1 mm for subsequent analyses and the formation of ceramic glazes. The WG sample was sieved to a size below 0.63 mm. The consistency of the glaze (fraction of slag + WG) was adjusted by adding water to achieve suspension and optimal rheological properties.

Suspensions of MF and NF with WG were deposited onto a ceramic substrate using a spray application method at ratios of 5/5 and 2/8 (fraction/waste glass). The selected ratios were based on previous experimental measurements performed on bulk samples, where standard parameters including frost resistance, chemical resistance, and heavy metal leachability were evaluated.

Milling and homogenization of the raw materials was performed using a vibratory disc mill BVM-2 (Brio Hranice s.r.o.). The firing process of glazed tiles was carried out using a laboratory furnace LAC (LAC s.r.o.). The chemical composition of the samples was determined by energy-dispersive X-ray fluorescence spectroscopy (ED-XRF) using a SPECTRO XEPOS instrument (Spectro Analytical Instruments, Kleve, Germany). The mineralogical composition was characterized by X-ray diffraction (XRD) analysis performed on a MiniFlex 600 diffractometer (Rigaku, Japan) equipped with a Co radiation tube and a D/teX Ultra detector. Diffraction patterns were recorded over a 2θ range of 5–90° at a scanning rate of 5° min⁻¹. The collected data were subsequently processed using HighScore software to identify the qualitative phase composition. Colour parameters of glazes were measured using a MiniScan EZ0828 spectrophotometer (HunterLab, 45°/0° geometry, small measurement area) according to the CIE Lab* colour space defined by the Commission Internationale de l'Éclairage (CIE). Measurements were performed at three different locations on the same sample, and the reported values represent the average of these measurements.

3. RESULTS AND DISCUSSION

3.1 Magnetic separation and chemical-phase composition

Prior to magnetic separation, the converter slag was divided into three particle-size fractions (<0.2 mm, 0.2–0.6 mm, and >0.6 mm) in order to evaluate potential size-dependent variations in chemical composition and to assess the feasibility of subsequent simple mechanical separation (e.g., sieving) as a complementary processing step. This approach also enabled assessment of whether particle-size classification alone could contribute to partial compositional pre-concentration.

The mass distribution of products obtained after VMS provides insight into the efficiency and selectivity of the applied method, as shown in **Figure 1**. **Figure 1** illustrates the mass proportions of magnetic and non-magnetic fractions obtained after VMS for each particle-size class. Although the non-magnetic fraction constituted the major mass proportion in each particle-size class, substantial recovery of iron-rich magnetic material was achieved across all fractions. The separation effect was particularly evident in the coarse fraction (>0.6 mm), where liberated iron-bearing particles were more readily captured.

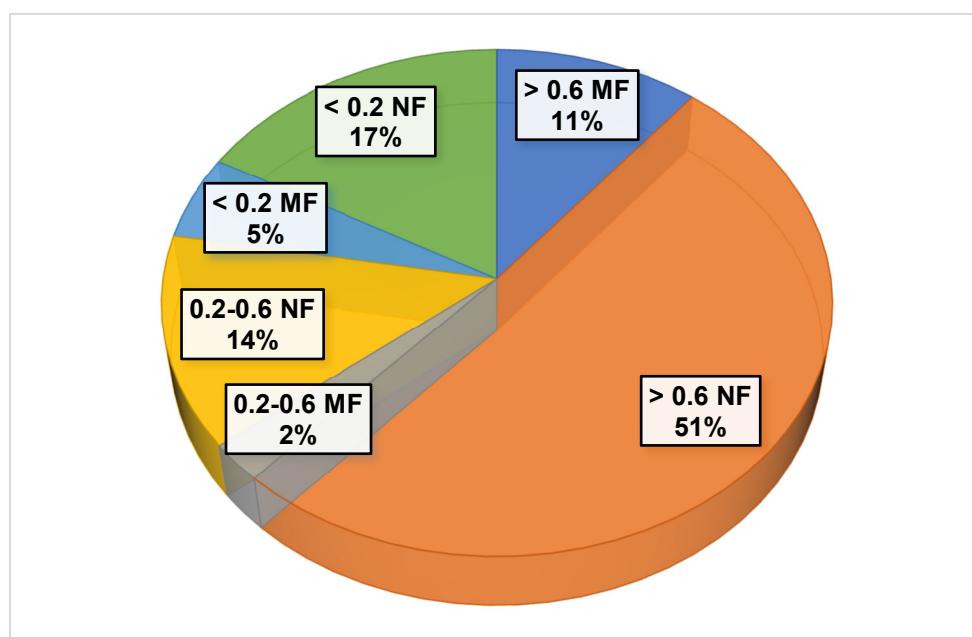


Figure 1 Percentage weight of individual magnetic fractions (MF) and non-magnetic fractions (NF) after VMS

The chemical compositions of the separated fractions, WG and CS (original composition of the slag before separation) are summarized in **Table 1**. Fe_2O_3 exhibited the most pronounced redistribution after separation. Its concentration increased to approximately 37-40 wt. % in all magnetic (MF) fractions, whereas the corresponding non-magnetic (NF) fractions contained 26-36 wt. %. This consistent enrichment across all particle-size classes confirms that Fe-bearing phases possess sufficiently high magnetic susceptibility to be selectively concentrated under vibrofluid conditions. The dynamic “granular gas” state generated during VMS enhances particle mobility, reduces particle friction, and promotes effective magnet-particle interactions within the bulk material, thereby improving separation selectivity compared to static magnetic systems.

In contrast, CaO was systematically enriched in the NF fractions, reaching up to 48.36 wt. % in the <0.2 mm fraction. Slightly elevated SiO_2 contents observed in NF fractions further support the preferential partitioning of Ca-Si mineral components into this stream. MnO followed a trend similar to Fe_2O_3 , with higher concentrations in MF fractions, suggesting partial incorporation of Mn into iron-bearing mineral structures. Other oxides showed only minor variations among fractions, indicating limited sensitivity to magnetic separation. Waste glass (WG) used in the glaze composition significantly influences the final properties of the glaze. Its high SiO_2 content promotes the formation of a glassy phase and enhances the surface gloss of the glaze.

X-ray diffraction analysis demonstrated that all fractions exhibit essentially identical qualitative phase composition, dominated by wustite (FeO), srebrodolskite ($\text{Ca}_2(\text{Fe,Al})_2\text{O}_5$), and larnite ($\beta\text{-Ca}_2\text{SiO}_4$), with minor amounts of free lime (CaO), mayenite ($\text{Ca}_{12}\text{Al}_{14}\text{O}_{33}$) and magnetite (Fe_3O_4). No new crystalline phases were generated during magnetic separation, confirming that VMS does not modify the mineralogical assemblage but redistributes pre-existing phases

Table 1 Chemical composition of magnetic (MF) and non-magnetic (NF) size fractions, CS and WG tested by XRF analysis

Fraction	NF > 0.6 mm	MF > 0.6 mm	NF 0.2-0.6 mm	MF 0.2-0.6 mm	NF < 0.2 mm	MF < 0.2 mm	CS	WG
MgO	5.14	3.62	3.10	3.06	2.50	2.13	2.97	3.13
Al ₂ O ₃	1.66	1.45	1.41	1.08	1.38	1.10	1.28	0.97
SiO ₂	8.85	7.74	7.52	6.58	8.69	6.44	7.29	68.06
P ₂ O ₅	1.16	1.18	1.01	1.11	0.94	1.00	1.05	-
SO ₃	0.39	0.36	0.52	0.42	0.53	0.58	0.52	0.53
CaO	40.87	39.43	45.39	38.90	48.36	41.42	45.62	15.57
TiO ₂	0.23	0.31	0.23	0.23	0.28	0.22	0.22	0.12
MnO	4.99	5.43	4.03	4.98	3.57	4.81	4.59	-
Fe ₂ O ₃	36.25	39.53	29.98	39.47	25.78	37.01	32.70	0.51
LOI-Flux	0.21	0.67	5.47	3.85	6.85	5.02	3.45	0.69

Taken together, the combined mass balance, chemical, and phase analyses demonstrate that vibrofluid magnetic separation enables selective redistribution of iron- and calcium-bearing phases within the slag matrix. The process therefore represents an effective pre-concentration strategy for targeted downstream utilization.

3.2 Characterization of coloured glazes

A total of 24 glaze formulations (G1-G24) were prepared from magnetic (MF) and non-magnetic (NF) slag fractions of three particle-size classes (>0.6 mm, 0.2-0.6 mm and <0.2 mm). The glazes were formulated at slag-to-waste-glass ratios of 5/5 and 2/8 and subsequently fired at 1,060 °C and 1,160 °C. The measured CIELab colour parameters (L*, a*, b*) are summarized in **Table 2-4**.

Across all formulations (G1-G24), L* values ranged from 26.87 to 64.45, indicating substantial variability in brightness. The lowest L* value (26.87) was recorded for glaze G7 (MF, >0.6 mm, 5/5) fired at 1,160 °C, whereas the highest brightness (L* = 64.45) was observed for glaze G22 (NF, <0.2 mm, 2/8) at 1,160 °C. The total brightness interval of 37.6 units confirms that magnetic separation, particle size, and formulation ratio collectively influence tonal development. Magnetic fractions generally yielded darker glazes compared to non-magnetic fractions. The darkest MF glaze (G7, L* = 26.87) exhibited approximately 28% lower brightness than the darkest NF glaze. In the finest fraction (<0.2 mm), the contrast between glaze G23 (MF, L* = 30.22) and glaze G22 (NF, L* = 64.45) exceeded 50%, representing the most pronounced MF–NF brightness difference within the dataset. The red coordinate (a*) ranged from 3.38 to 11.66. The highest a* value (11.66) was recorded for glaze G23 (MF, <0.2 mm, 5/5), whereas the maximum NF value (10.04) occurred for glaze G5 (>0.6 mm, 5/5), corresponding to an approximately 16% higher red contribution in the most saturated MF glaze. The yellow coordinate (b*) showed the most pronounced temperature-dependent variation, ranging from 9.80 to 41.09. The highest b* value (41.09) was observed for glaze G8 (MF, >0.6 mm, 2/8) fired at 1,160 °C. In this formulation, b* increased from 14.33 at 1,060 °C (G4) to 41.09 at 1,160 °C (G8), representing an increase of approximately 187%. A similarly strong increase was observed for glaze G6 (NF, >0.6 mm, 2/8), where b* reached 39.41 at 1,160 °C. Particle size also influenced colour variability. The coarse fraction (>0.6 mm) produced the highest maximum b* values (G8, b* = 41.09). The intermediate fraction (0.2–0.6 mm) yielded the highest individual L* value (G10, L* = 63.69). The finest fraction (<0.2 mm) exhibited the widest brightness interval, from G23 (L* = 30.22) to G22 (L* = 64.45).

Table 2 *CIE*Lab colour parameters (L^* , a^* , b^*) of glazes prepared from >0.6 mm magnetic (MF) and non-magnetic (NF) slag fractions fired at 1,060 °C and 1,160 °C

Temperature	1,060 °C				1,160 °C			
Glaze	G1	G2	G3	G4	G5	G6	G7	G8
Materials	NF/WG	NF/WG	MF/WG	MF/WG	NF/WG	NF/WG	MF/WG	MF/WG
Ratio	5/5	2/8	5/5	2/8	5/5	2/8	5/5	2/8
Visual tone								
L^*	41.92	40.03	36.76	35.99	45.19	49.26	26.87	41.75
a^*	4.39	6.87	3.84	7.13	10.04	9.00	10.21	11.45
b^*	13.12	15.48	12.52	14.33	31.10	39.41	21.67	41.09

Table 3 *CIE*Lab colour parameters (L^* , a^* , b^*) of glazes prepared from 0.2–0.6 mm magnetic (MF) and non-magnetic (NF) slag fractions fired at 1,060 °C and 1,160 °C

Temperature	1,060 °C				1,160 °C			
Glaze	G9	G10	G11	G12	G13	G14	G15	G16
Materials	NF/WG	NF/WG	MF/WG	MF/WG	NF/WG	NF/WG	MF/WG	MF/WG
Ratio	5/5	2/8	5/5	2/8	5/5	2/8	5/5	2/8
Visual tone								
L^*	43.30	63.69	43.43	50.80	40.63	62.02	41.59	51.50
a^*	4.25	6.82	5.30	7.03	9.39	5.70	11.41	9.05
b^*	11.10	18.89	15.24	16.79	31.41	31.24	36.97	39.92

Table 4 *CIE*Lab colour parameters (L^* , a^* , b^*) of glazes prepared from <0.2 mm magnetic (MF) and non-magnetic (NF) slag fractions fired at 1,060 °C and 1,160 °C

Temperature	1,060 °C				1,160 °C			
Glaze	G17	G18	G19	G20	G21	G22	G23	G24
Materials	NF/WG	NF/WG	MF/WG	MF/WG	NF/WG	NF/WG	MF/WG	MF/WG
Ratio	5/5	2/8	5/5	2/8	5/5	2/8	5/5	2/8
Visual tone								
L^*	50.06	51.83	43.30	47.49	37.88	64.45	30.22	61.78
a^*	3.38	4.67	4.33	4.33	9.40	4.26	11.66	5.26
b^*	9.80	12.72	11.32	11.87	31.41	28.34	31.66	31.86

In addition to colour differences, distinct surface characteristics were observed depending on formulation ratio and firing temperature. All glazes formulated at a 5/5 slag-to-waste-glass ratio and fired at 1,060 °C (G1, G3, G9, G11, G17 and G19) exhibited a powdery surface and are therefore not suitable for practical glaze applications. In contrast, all glazes formulated at a 2/8 ratio and fired at 1,060 °C (G2, G4, G10, G12, G18 and G20) displayed a glossy surface. The remaining formulations, including all samples fired at 1,160 °C, exhibited

stable tactile (matte to semi-matte) surface characteristics. When appropriate slag-to-waste-glass ratios and firing temperatures are applied, both magnetic and non-magnetic slag fractions can be effectively incorporated into ceramic glaze systems.

4. CONCLUSION

The present study demonstrated that vibrofluid magnetic separation represents an effective method for the phase–chemical redistribution of converter steel slag and enables selective concentration of iron-bearing phases. Magnetic fractions showed significant enrichment in Fe_2O_3 (approximately 37-40 wt. %), confirming the high magnetic susceptibility of iron-containing minerals, whereas non-magnetic fractions were enriched in CaO and silicate phases. Mineralogical analysis indicated that the separation process did not alter the qualitative phase composition but redistributed existing mineral phases within the material.

Both magnetic and non-magnetic fractions were successfully applied as secondary raw materials in ceramic glaze formulations combined with waste glass. The prepared glazes exhibited a wide range of colour tones and brightness values, strongly influenced by iron content, particle size, formulation ratio, and firing temperature. Magnetic fractions generally produced darker and more reddish-brown colours, while non-magnetic fractions resulted in brighter glazes. It should also be noted that the glaze colour differs among the individual fractions; however, from the user's perspective, the overall range of shades remains consistent. This characteristic may be advantageous for ensuring repeatability and consistency in glaze production when using this type of converter slag.

The experimental results confirm that converter slag can be effectively valorised through combined magnetic separation and ceramic processing. This approach enables simultaneous recovery of iron-rich fractions for potential metallurgical reuse and utilization of the remaining material in value-added ceramic products. Consequently, the proposed processing route contributes to the comprehensive utilization of steel slag and supports circular economy principles by reducing industrial waste and promoting sustainable material recycling.

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