# Using magnetic separation to recover iron from steel slag

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## Summary

*The study investigates the recovery of iron from steel slag using two different approaches: vibrofluid magnetic separation (VMS) and wet magnetic separation (WMS). VMS achieved a high iron concentration in the magnetic fraction (55.08 wt. % $Fe_2O_3$), demonstrating the potential of this method to selectively capture iron-rich particles without the use of water. However, the total amount of magnetic concentrate obtained by VMS was low. Manual magnetic separation yielded additional fractions, but these contained lower Fe concentrations. In contrast, WMS reached* 32.23 *wt. % $Fe_2O_3$ in the magnetic fraction, but captured almost half of the sample, resulting in lower overall selectivity.*

**Keywords:** *Steel slag, magnetic separation, iron, recovery, $Fe_2O_3$.*

## Introduction

Steel slag is a major industrial by-product generated during steelmaking, representing about 10 – 15% of crude steel output[1]. While developed regions such as Europe and the United States achieve utilization rates of 80 – 90 %, in many countries most of the slag is still stockpiled or landfilled, leading to resource loss and environmental concerns[2,3].

Steel slags (SS) differ from blast furnace slag (BFS) in their chemical and mineralogical variability, which complicates their direct application[4]. They contain valuable components including Fe, CaO, $SiO_2$, and $P_2O_5$, but also potentially harmful heavy metals such as Cr, Cd, and Pb[5]. Based on their production routes, steel slags are classified into steel slag (FS) and ladle slag (LS). While BFS has long been widely used in cement and construction industries, FS and LS are more often stockpiled or landfilled, causing land occupation and environmental pollution[6].

Owing to their Fe-rich composition, the recovery of metallic iron and iron oxides is a key pathway for steel slag valorization. Typically, wet magnetic separation (WMS) has been employed to recover Fe phases, but this method suffers from limited recovery efficiency (60 – 65%) and high-water consumption[7,8]. In contrast, dry magnetic separation (DMS) techniques, including pneumatic magnetic separators (PMS) and fluidized magnetic separators (FMS), have shown promise in overcoming problems such as agglomeration of fine particles and improving selectivity[9-11]. Complementary strategies such as oxidative modification, controlled cooling, or the addition of modifiers ($SiO_2$, $TiO_2$, $Al_2O_3$) can further enhance Fe recovery[12-14].

Besides metallurgical recycling, steel slag has been investigated as a cementitious material due to the presence of minerals such as dicalcium silicate ($C_2S$), tricalcium silicate ($C_3S$), and dicalcium ferrite ($C_2F$), which account for over 45% of its composition and resemble those in Portland cement clinker[15]. However, the coexistence of inert phases and free-CaO significantly reduces its hydration activity and long-term stability[16,17]. Activation methods including mechanical grinding[18], chemical activation[19], carbonation[20], and high-temperature reconstruction[21] have been tested, but their effectiveness remains limited.

Therefore, developing efficient, low-cost, and environmentally friendly technologies for the recycling and utilization of steel slag is of great importance. Integrating advanced DMS systems with slag modification strategies could simultaneously enhance iron recovery and enable the use of residual slag as a supplementary material in construction, thereby promoting sustainable steel production[22].

## Experimental part

### *Procedure description*

The sample SS (steel slag) was dried at 105 °C for 3 hours (the weight difference was stable), where it was subsequently cooled in a desiccator and weighed. Subsequently, the steel slag sample was ground in a vibrating disc mill for 2 minutes and the entire sample content was manually sieved to a size of less than 0.1 mm. The sieving and grinding process was repeated until the entire content was sieved below 0.1 mm.

In this study, two types of magnetic separation were tested: dry magnetic separation in a vibrofluid state (VMS – vibrofluid magnetic separation) and wet magnetic separation using a magnetic bar (WMS – wet magnetic separation).

VMS was used to induce the “granular gas” state in the slag sample, preventing particle cohesion and enabling selective separation. This approach allows separation to occur in the bulk volume rather than in thin layers (as used in manual separation), thereby improving process efficiency. The method increases both selectivity and efficiency.

In this method (VMS), 100 g of sample was spread over a large area in a very thin layer on the base of a laboratory sampler. The distance between the magnet and the sample layer was 3 cm (±1 cm), and the magnet was placed exactly in the center of the device. For 2 minutes, the sample was exposed to the vibrational forces of a modified laboratory vibrating device, in which a permanent magnet with a breaking force of 21 kg was installed. The magnet placed in the middle of the device held the second magnet through the plexiglass. After the separation, the upper magnet was removed, releasing the lower magnet with the sample. The fraction separated in this way was designated as VMF in the study.

The VMS residue was manually (by hand) passed through a permanent magnet (the sample distance from the magnet was 3 cm) with a breaking force of 21 kg. This step separated a fraction designated MMF – magnetic manual fraction.

After manual magnetic separation, a layer of aggregated gray particles formed on the surface of the sample residue, was collected. These particles were aggregated on top of the rest of the sample due to the force of the magnet but could not be captured by the magnet due to their size or nature. This step produced two fractions: a fraction containing gray aggregated particles on the surface of non-magnetic fraction (FAP) and the total residue (TR), which was obtained after careful removal of the aggregated particles (mechanically removed sample with a laboratory spoon).

Wet magnetic separation experiments were carried out in a glass beaker. Approximately 5 g of slag was dispersed in 300 mL of deionized water and homogenized by stirring for 1 min. A neodymium magnet encased in a stainless-steel tube (rod diameter: 25.4 mm, total length: 406 mm and maximum tearing force 1.4 kg) was subsequently introduced into the suspension. Magnetic particles were collected on the rod surface, removed, and retained as the magnetic concentrate. Both fractions were dried. The separation procedure was repeated. The resulting magnetic fraction was designated as WMF and the non-magnetic fraction as WNF in this study.

### *Characterization methods*

The chemical composition of sample was determined by a method of energy-dispersive X-Ray fluorescence spectroscopy (ED-XRF) on the SPECTRO XEPOS (Spectro Analytical Instruments, Kleve, Germany). The iron content was determined by the standard ISO 2597-2:2019.

The mineralogical composition of the samples was determined using X-ray diffraction analysis (XRD) performed on a MiniFlex 600 diffractometer equipped with a Co tube and a D/teX Ultra detector. Diffraction patterns were collected within the 2θ range of 5 – 90° at a scanning speed of 5°/min (Rigaku, Japan). The XRD data obtained were processed using the Highscore software to identify the qualitative phase composition.

The particle size distribution and specific surface of steel slag sample was determined using a Malvern Instrument device with the Aero method, covering a range of 0.1 – 10000 μm (Malvern Panalytical Ltd., Malvern, UK).

## Results and discussions

### Particle size distribution

The particle size distribution determines how efficiently iron can be released from the slag and how reliably the magnet can capture it. For a clearer overview and comparison, the parameters of slag sample (SS) were plotted in Table 1.

Sample SS was characterized by finer particle sizes, with Dv10, Dv50, and Dv90 values of 1.48 μm, 8.35 μm, and 47.4 μm, respectively. The Sauter mean diameter (D [3.2]) was 3.51 μm, while the volume-weighted mean diameter (D [4.3]) reaches 18.7 μm. The specific surface area of this sample was relatively low (1179 m²/kg). Furthermore, the high span (5.499) and uniformity index (1.814) confirm the heterogeneous nature of the material.

***Table 1. Particle size distribution parameters of steel slag sample SS***

| **Parameter** | **SS** |
|---|---|
| **Dv (10)** (μm) | 1.48 |
| **Dv (50)** (μm) | 8.35 |
| **Dv (90)** (μm) | 47.4 |
| **D [3,2]** (μm) | 3.51 |
| **D [4,3]** (μm) | 18.7 |
| **Specific Surface Area** (m²/kg) | 1179 |
| **Span** | 5.499 |
| **Uniformity** | 1.814 |

### Chemical composition

The chemical composition of sample SS is shown in the Table 2. Chemical composition was dominated by CaO (47.93 wt. %) and $Fe_2O_3$ (29.73 wt. %). Significant amounts of $SiO_2$ (9.40 wt. %) and MnO (4.38 wt. %) were also present. Minor oxides included MgO (3.57 wt. %) and $Al_2O_3$ (1.53 wt. %), while $SO_3$ (0.14 wt. %) occurred only in trace levels. This composition of steel slag also corresponds to the studied slags from foreign sources, where the CaO content ranges between 42 and 55 wt. % and the $SiO_2$ content between 10 and 18 wt. %[23]. Depending on the efficiency of the furnace, the iron oxide ($FeO/Fe_2O_3$) content of steel slag can be as high as 38%[24].

***Table 2: Chemical compositions of sample SS***

| **Oxides** (wt. %) | **MgO** | **$Al_2O_3$** | **$SiO_2$** | **CaO** | **$SO_3$** | **MnO** | **$Fe_2O_3$** |
|---|---|---|---|---|---|---|---|
| | 3.57 | 1.53 | 9,40 | 47.93 | 0.14 | 4.38 | 29.73 |

### Mineralogical composition

XRD revealed (Figure 1) that the analyzed SS sample consists of a complex mixture of crystalline phases. The identified phases include iron oxides (Wüstite and magnetite), lime, larnite, Srebrodolskite and mayenite. The coexistence of Wüstite and magnetite indicates a redox equilibrium between Fe(II) and Fe(III) during slag solidification[25], while the detection of CaO reflects incomplete reactions during smelting and suggests potential reactivity upon hydration. Phases such as larnite, mayenite, and srebrodolskite correspond to high-temperature products of the $CaO–SiO_2–Al_2O_3–FeO$ system, and they are known carriers of latent hydraulic activity[26].

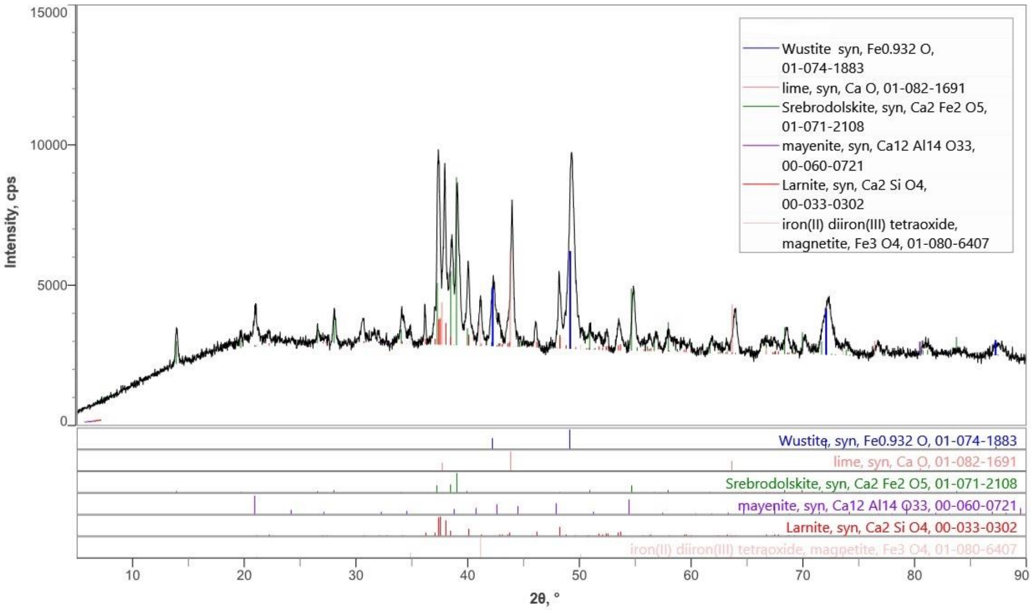

***Figure 1**: XRD pattern of sample SS*

### *Magnetic separation*

The mass yields of the obtained fractions are illustrated in Figure 2, while the $Fe_2O_3$ contents of the fractions are summarized in Tables 3 and 4.

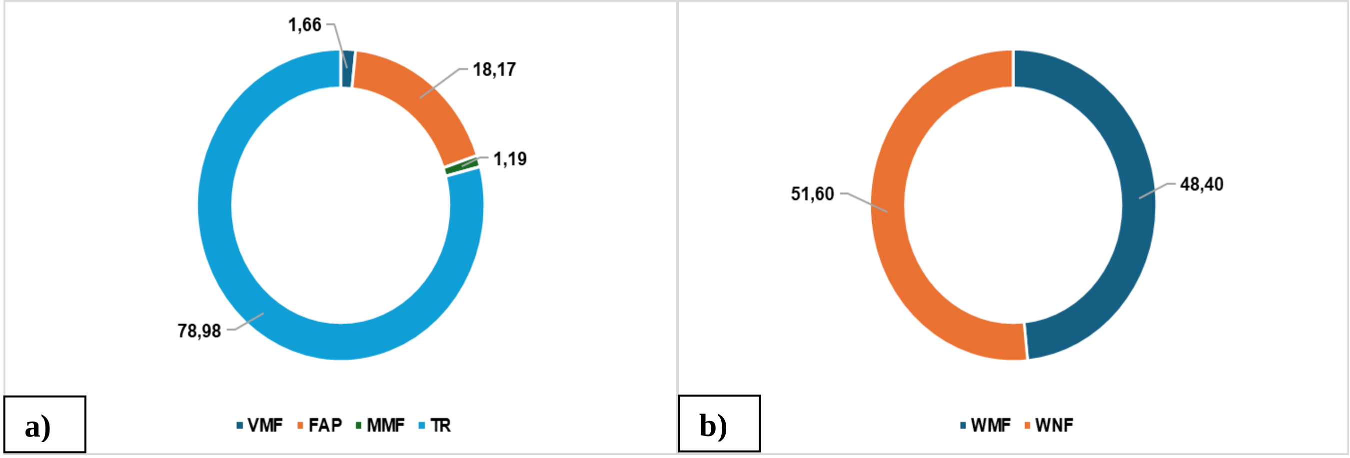

***Figure 2**: Representation of individual mass yields (wt. %) after separation steps of vibrofluid magnetic separation (a) and wet magnetic separation (b) of sample SS (VMF =vibrofluid magnetic fraction, FAP = aggregated particles fraction, MMF = magnetic manual fraction, TR = total residue, WMF = wet magnetic fraction and WNM = wet non-magnetic fraction)*

During VMS, the sample SS was divided into several distinct fractions. The highest $Fe_2O_3$ concentration was recorded in the vibrofluid magnetic fraction (VMF, 55.08 wt. %), demonstrating the high efficiency of this method in capturing iron-rich particles. The manually separated magnetic fraction (MMF) contained a lower $Fe_2O_3$ concentration (39.19 wt. %), indicating the presence of less pure magnetic grains. The fraction of aggregated particles (FAP) showed an $Fe_2O_3$ content of 30.08 wt. %. The lowest concentration was found in the total residue (TR, 28.09 wt. %), which is expected since most magnetically active particles had already been removed.

In the case of wet magnetic separation, the sample was separated into two fractions. The magnetic fraction (WMF) contained a high $Fe_2O_3$ concentration of 32.23 wt. %, while the non-magnetic fraction (WNF) exhibited a significantly lower value of 27.60 wt.%.

***Table 3. $Fe_2O_3$ contents in the prepared fractions after dry vibrofluid magnetic separation SS (VMF =vibrofluid magnetic fraction, FAP = aggregated particles fraction, MMF = magnetic manual fraction and TR = total residue)***

| **Fractions** | **$Fe_2O_3$** (wt. %) |
|---|---|
| **VMF** | 55.08 |
| **MMF** | 39.19 |
| **FAP** | 30.08 |
| **TR** | 28.09 |

***Table 3. $Fe_2O_3$ contents in the prepared fractions after wet magnetic separation (WMF = wet magnetic fraction and WNM = wet non-magnetic fraction)***

| **Fractions** | **$Fe_2O_3$** (wt. %) |
|---|---|
| **WMF** | 32.23 |
| **WNF** | 27.60 |

This result confirms the effectiveness of the wet method, but due to the very strong magnet, a large part of the sample was captured – almost half, so the Fe content was not too high.

## Conclusions

The results highlight that vibrofluid separation provides a relatively high-grade magnetic concentrate with the advantage of avoiding wastewater generation and additional drying costs, making the material more directly usable. Its main drawback is the low yield of magnetic concentrate. Wet magnetic separation, on the other hand, recovered a much larger portion of the sample, but with lower selectivity due to the strong magnet used, reducing the Fe content of the concentrate. Future experiments should therefore focus on optimizing magnet strength in WMS to increase iron enrichment while maintaining efficiency.

## List of symbols

BFS – Blast furnace slag
DMS – Dry magnetic separation
ED-XRF – Energy-dispersive X-ray fluorescence spectroscopy
FAP – Fraction of aggregated particles
FMS – Fluidized magnetic separator
FS – Furnace steel slag
LS – Ladle slag
MMF – Magnetic manual fraction
PMS – Pneumatic magnetic separator
SS – Steel slag
TR – Total residue
VMS – Vibrofluid magnetic separation
VMF – Vibrofluid magnetic fraction
WMF – Wet magnetic fraction
WMS – Wet magnetic separation
WNF – Wet non-magnetic fraction
XRD – X-ray diffraction

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# Použití magnetické separace k získávání železa z ocelové strusky

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## *Abstrakt*

*Studie zkoumá zpětné získávání železa z ocelové strusky pomocí dvou různých přístupů: vibrofluidní magnetické separace (VMS) a mokré magnetické separace (WMS). VMS dosáhla vysoké koncentrace železa v magnetické frakci (55,08 hmot. %* $Fe_2O_3$*), což demonstruje potenciál této metody selektivně zachytit částice bohaté na železo bez použití vody. Celkové množství magnetického koncentrátu získaného pomocí VMS však bylo nízké. Manuální magnetická separace přinesla další frakce, ale ty obsahovaly nižší koncentrace Fe. Naproti tomu WMS s velmi silným magnetem dosáhla 55,08 hmot. %* $Fe_2O_3$ *v magnetické frakci, ale zachytila téměř polovinu vzorku, což vedlo k nižší celkové selektivitě.*

**Klíčová slova:** *Ocelová struska, magnetická separace, železo, regenerace,* $Fe_2O_3$*.*