

# Editorial for Special Issue “Metallurgical Slags”

Jakub Kierczak <sup>1,\*</sup>  and Vojtěch Ettler <sup>2</sup> 

<sup>1</sup> Institute of Geological Sciences, University of Wrocław, Pl. M. Borna 9, 50-205 Wrocław, Poland

<sup>2</sup> Institute of Geochemistry, Mineralogy and Mineral Resources, Faculty of Science, Charles University, 128 43 Prague 2, Czech Republic; vojtech.ettler@natur.cuni.cz

\* Correspondence: jakub.kierczak@uwr.edu.pl

Exploitation and further processing of mineral resources are of great importance for modern society. However, these processes are accompanied by the production of a variety of by-products. Metallurgical slag, formed during the smelting of metallic ores or/and secondary raw materials such as scrap or waste batteries, is one of the most abundant.

Over the past several decades, there has been a growing interest in research on metallurgical slags. The keyword ‘slag’, entered in the Web of Science database, returns over 38,000 publications (as of mid-December 2020). Also, the number of publications has been increasing over the last 20 years [1]. This shows that slag oriented research has been a hot topic for some time now. Based on the Web of Science database, which assigns publications to different sub-subject categories, it can be concluded that most of the research on slags is focused on their reuse as raw material and their impact on the environment.

When planning this Special Issue, our goal was to collect scientific articles presenting the current state of knowledge and different approaches to the research on metallurgical slags. Multidisciplinary studies of metallurgical slags published in this issue are mostly focused on: (1) their reuse as secondary raw materials, (2) assessing the risk they may pose to the environment, and (3) the study of traces of ancient metallurgy.

In this Special Issue, we have collected 13 articles; the two first papers have focused on the stability of metal-bearing phases in different conditions. The study of Zhao et al. [2] addresses the influence of lime on the stability of Cr in the stainless steel slag. Through the experimental approach, the authors showed that the Cr distribution among phases identified in the slag depends on the CaO/SiO<sub>2</sub> ratio (slag basicity). Also, the optimal basicity for which Cr is the most stable and bound in spinels was estimated at 1.5. The stability of Cr in steel slags was also investigated by Zhao et al. [3]. In this study, phase composition and Cr distribution in steel slags were studied under various cooling regimes. The authors concluded that quenching of the slag at 1300 °C causes most of the Cr to be present in highly resistant spinel phases. These studies show that it is important to develop an appropriate technology during slag formation to make it an environmentally safe material with the potential to be reused.

The contribution by Pietranik et al. [4] emphasizes the difficulties that commonly occur in an attempt to accurately determine the phase composition of highly weathered slags. Through the study of a Technosol occurring on a slag heap, the authors developed a five-step methodology to estimate the presence and proportions among minerals of detrital, primary, and secondary origin. They concluded that this approach could be successfully used for rapid recognition of the slag-derived as well as allogenic phases in a complex setting and for the reconstruction of the intensity of slag weathering at a given site.

The paper of Wenkh et al. [5] focused on the characterization of historical slags located in the vicinity of the Casaccia site (Swiss Alps) using modern mineralogical methods. The studied slags were identified as by-products of Cu metallurgy and, based on their mineralogical and geochemical characteristics, represent most probably metallurgical remnants of the Late Bronze Age. This preliminary study can be treated as an inspiration for more systematic archeometric studies to trace back the evolution of metallurgy in Val Bregaglia.



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In the study of historical slags issued from the processing of Pb, Ag, and Cu ores in western Tasmania by Parbhakar-Fox et al. [6], a range of analytical techniques enabled the identification of metal-bearing phases. The authors showed that these slags contain elevated concentrations of metallic elements (especially Zn) and are classified as potentially acid-forming; therefore, they constitute a risk for the environment. It was concluded that a reprocessing of these slags for Zn extraction is a viable option.

Another example of how to reuse metallurgical slags is presented in the contribution of Piatak et al. [7]. Through the study of ferrous slags from the Chicago-Gary area (Illinois and Indiana, USA), the effective removal of phosphates from solution was documented. Also, the studied slags had high acid neutralization potential. The authors concluded that the slags are better suited for water treatment than for construction purposes.

The contribution of Neuhold et al. [8] demonstrates the use of the multi-methodological approach to study the leachability of electric arc furnace slags with special attention to Cr and V. The authors identified the Cr and V phases in the studied slags as well as their stability during leaching experiment. Based on the combined approach used in this study, it was found that the phase composition and leachability of Cr and V are influenced by the FeO/SiO<sub>2</sub> and CaO/SiO<sub>2</sub> ratios. Therefore, properly modified proportions of these components will minimize the risk related to the release of contaminants present in these slags.

The feasibility of (bio)hydrometallurgical methods for metal extraction from historical Cu slags was evaluated by Potysz and Kierczak [9]. Two distinct slag types were subjected to the leaching using several different solutions, with those containing *Acidithiobacillus thiooxidans* being the most effective. The main conclusion drawn from the conducted research was that the texture of slag was the main factor influencing their dissolution since amorphous slag was more susceptible to leaching than crystalline. Also, the former was indicated as potentially viable for metal recovery.

The study of Soultana et al. [10] is aimed at determining the optimal conditions for the production of inorganic polymers based on ferronickel slag and brick wastes. The experimental approach revealed that the highest compressive strength had been achieved for the material produced using a mix ratio of 50 wt % metallurgical slag and 50 wt % brick wastes, cured at 90 °C and aged for seven days. These optimum conditions have also been confirmed by detailed microstructural analyses of the polymers. Also, in this paper, the authors concluded that the reuse of slag is a viable alternative for the production of valuable construction materials.

It is essential to have detailed knowledge about the distribution of potentially valuable elements to develop an appropriate method of their recovery from metallurgical slags. In this context, Horckmans et al. [11] studied the concentration and distribution of Cr in several types of ferrous slags. Based on the multi-analytical approach, it was found that the small size of spinels, principal Cr-carriers, may hinder the recovery of this element. Also, it was shown that spinels as highly resistant to dissolution might not be completely dissolved in acids, and other leaching solutions, e.g., sodium peroxide, should be considered.

The contribution of Mombelli et al. [12] investigates the impact of the tapping method on the stabilization treatment of electric arc furnace carbon steel slags. It was noted that cooling in the slag pot improved the stabilization efficiency through the formation of coarse-grained texture. On the other hand, rapid slag stabilization in the pit reduced its interaction with the stabilizer and resulted in finer-grained texture and inhomogeneity of the slag. Therefore, to use the slag as raw material, it is necessary to properly plan the methods of their stabilization.

A detailed study of sulfides occurring in the historical (Bronze Age) Cu slags from South Urals and Kazakhstan was presented in the paper of Artemyev and Ankushev [13]. By analyzing the content of trace metals in Cu-Fe sulfides (covellite, chalcocite, bornite, and chalcopyrite), the authors determined the origin of the Cu deposits, the exploitation of which left slags. This research is an example of how the methods used in mineralogy can be successfully used to solve the puzzles that archaeologists usually struggle with.

Finally, the study of Li et al. [14] focused on the reduction and liquidus behavior of manganese slags with different basicities. To study reduction rates, the authors performed experiments on two types of ores (Assmang ore from South Africa and Comilog ore from Gabon) with a continuous temperature increase under CO atmospheric pressure and fixed basicity. It was shown that Comilog slags had a much higher reduction rate than Assmang slags.

Overall, the papers published in this Special Issue present various perspectives and approaches to the studies of metallurgical slags. Most of them focus on the use of slags as raw materials while not forgetting their potential negative impact on the environment. These studies on slags provide a valuable source of information on former exploitation and historical smelting technologies. However, all the discussed publications have one thing in common, namely that the basic research methods used in the slag studies are similar to those used in the studies of rocks and minerals. Therefore, despite slags not being composed of minerals, they fit perfectly into the scope of the *Minerals* journal.

**Conflicts of Interest:** The authors declare no conflict of interest.

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