Proceedings of the 25th Annual British Columbia Mine Reclamation Symposium in Campbell River, BC, 2001.
The Technical and Research Committee on Reclamation

SLAG RECLAMATION IN THE 21ST CENTURY

Vinay Chaskar and Bern Klein

Department of Mining and Mineral Process Engineering, The University of British Columbia

Vancouver, B.C., V6T 1Z4

Abstract: A plan of action is proposed to develop uses of non-ferrous slag and production of certain industrial materials from this waste material. A review of chemistry of non-ferrous slags suggested that it can be reprocessed to impart "cementitious" properties and furthermore an advantage could be taken of their latent "pozzolonaic" properties to test several potential applications such as - clinker ingredient, asphalt concrete additive, cemented mine backfill and binder for base stabilization. The authors note that in the last century blast furnace slag was considered as a "waste" product whose stocks grew at an alarming rate due to decades of accumulation and iron producers had to develop uses of this material to avoid a potentially catastrophic environmental situation. Non-ferrous slag producers could emulate this example set by the iron producers who successfully converted a "waste" into a "byproduct". Environmental concerns of the new millennium demand that the industry should find ways and means of depleting the ever-growing stockpiles of non-ferrous slag. The authors conclude that serious considerations from environmental and economic fronts favor reclamation of old slag dumps as well as processing of new non-ferrous slag as a viable alternative to the existing dumping practice.

1. Introduction

Slags are inevitable byproducts of high temperature processing of metallic ores. During the extraction of non-ferrous metals - Nickel, Copper, Lead and Zinc and in the production of Iron and Steel, large quantities of slag are generated. Usually considered as a waste, these slags are often "dumped" in the proximity of smelters and receive no further treatment.

Historically, the metal industry has generated more ferrous slag than the non-ferrous slag and the ratio of the quantities of two slags has often exceeded 5. The slag generated by Iron and Steel producers is classified as ferrous slag and its annual worldwide production is estimated in the range of 250-280 million tonnes. (Réf. 1) -Although a similar data is not available for non-ferrous slags, which are produced by nickel, copper, lead and zinc industries, a conservative estimate could approach 50 million tonnes per annum. For example, in Canada alone over 4 million tonnes of slags are generated annually. (Ref. 2)

In British Columbia, there are at least three locations where large quantities of slag are stockpiled. All the three slags fall in the non-ferrous category. Out of these three locations, the two namely, Anyox and (Stand Forks represent abandoned sites of old untreated material whereas at the Trail location the slag stockpile is accumulating due to the ongoing lead and zinc smelting operations. Additional information on these slags is provided in a separate section of this paper.

In the ferrous slag category, which consists of blast furnace slag (BFS) and steel slag (SS), the blast furnace slag production has always exceeded that of steel slag. As a consequence huge stockpiles of this waste material were generated especially in the early decades of the last century. In the 1940s the iron producers acknowledged the need to utilize BFS slag in an attempt to avert potential catastrophic consequences resulting from its unabated accumulation. Although initially the blast furnace slag (BFS) was used only as a rail ballast and road base material, many researchers focused efforts in the 1960s and 1970s to promote acceptance of BFS as a "concrete aggregate". In the early 1980s, ASTM standards were developed as the demand for the product was growing consistently and the stockpiles of this material started to deplete for the first time. Increasingly the fresh blast furnace slag found its way to the market instead of ai dump, essentially culminating the transition of "waste" into a "byproduct". With better understanding of the interrelationships between slag chemistry, mineralogy and important physical properties - such *as* density, porosity and hardness, slag processors began to offer specific products that met requirements of many end users.

It is interesting to note that the non-ferrous slag producers have not emulated the example set by the iron producers in reversing the trend of slag accumulation in spite of some similarity in the chemical compositions between the two slags. A review of literature (Ref. 3-7) reveals that following the successful implementation of BFS usage, the construction industry has tested two other recycled products - fly ash and silica fume for their consumption. The use of these materials as an admixture has been accepted in many applications.

IQ many countries several millions of tonnes of slag has been accumulated, occupying vast areas of land, as a result of extraction and smelting operations for the past several decades. Needless to say, such a mode of slag disposal is not favored in the current climate of ever increasing environmental awareness. Furthermore, disposal of hot molten slag poses additional safety concerns and since costs are inevitably incurred in its handling, the dumping practice needs to be scrutinized from economical as well as environmental perspectives.

2. Composition of Non-Ferrous Slags

Chemical composition of both *the* ferrous and non-ferrous slags is dominated by 4 or 5 oxide species namely - silica, lime, alumina, iron oxide and magnesia, together constituting up to 95% of its composition. The major difference between the ferrous and non-ferrous slags is in the proportion of iron oxide species. The non-ferrous slags contain substantially higher proportions of iron oxide (between 40 to 50%) compared to ferrous slags (about 20% in SS and < 2% in BFS). However, a common feature of both types of slags is that during smelting they are molten and form two distinct layers. Slag is the lighter of the two phases, and floats over top of the underlying metal-containing phase allowing easy separation from the molten bath for disposal purposes.

Table 1 shows that essentially the composition of non-ferrous slag can be considered as a mixture of different proportions of BFS, fly ash and silica fume and for this reason its usage as a concrete admixture or a supplementary cementing material is feasible.

Table 1. Typical assays of non-ferrous slag, portland cement and supplementary materials. (Réf. 6-8)

Chemical Species	Non-ferrous Slag	Portland Cement	Supplementary Cementing Materials		
			BFS	Fly Ash	Silica Fume
% SiO_2	20 – 40	20 – 22	32 – 42	45 – 50	88 – 92
% Al_2O_3	3 – 10	4 – 6	7 – 16	16 – 25	< 2
% Fe_2O_3	-	2 – 4	< 2	7 – 26	3 – 5
% FeO	40 – 55	-	-	-	-
% CaO	2 – 20	60 – 65	32 – 45	4 – 8	< 2
% MgO	2 – 3	1 – 4	3 – 12	1 – 5	< 1
Other oxides	< 5	< 2	< 2	< 1	< 1

Upon examination these compositions it is tempting to ask the following question:

Why are the non-feirous slags considered as a waste material?

Comparison between Portland cement and non-ferrous slag assay reveals that a hypothetical replacement of FeO by CaO will convert the slag to Cement. Although in reality such a replacement is inconceivable it does imply a certain similarity in the characteristics of these two materials. Furthermore, in chemical terms both the FeO and CaO are considered as basic oxides and are expected to display compatibility in terms of many other properties. In fact, a variety of slag treatment techniques were developed based on this chemical compatibility; mainly to recover the entrained metallic values from the non-ferrous slags. Many references can be sighted on this subject matter (Réf. 8 - 10); however, a further discussion on this topic is beyond the «cope of present paper.

3. Recycling Options for Non-ferrous Slag

Review of (existing disposal practices reveals that the hot molten slag is either granulated using water jets/sprays or dumped in a specific area and allowed to cool in air. The former is a controlled cooling method as opposed to the latter where the rate of cooling is not controlled. Although in both instances certain costs are incurred by handling of slag, very little or no attention is paid to the material accumulated as a stockpile. In a few isolated cases the industry did choose to retreat the stockpiled slag for the purposes of «covering entrained metal values.

It is important to note that in all the instances in the past where the non-ferrous slag was processed, the impetus for such a treatment was mainly "economic" and the environmental concerns played very little role, if any. The operation was usually termed as "slag cleaning" and the main goal was the recovery of metallic values. Often, the process generated more slag, due to additions of flux or other ingredients to enhance the metal recovery, which ended up at the dump. This trend has persisted for the past several decades and even today, the non-ferrous slag is primarily considered as a waste material with only minor quantities used as rail ballast and fill material.

The two main reasons usually sighted for gross under-utilization of non-ferrous slags are:

(1) Remote locations of slag producing smelters with respect to potential markets, and
(2) Wide variations in then" chemical and physical properties.

Needless to say, growing concerns of environmental degradation due to solid waste disposal together with heightened awareness with regard to its potential adverse effects are forcing many industries to reconsider their priorities and take a serious second look at possible options to reduce these wastes. Company policies with regard to the slag storage are increasingly coming under scrutiny by various governmental agencies and additionally, many governments are pushing for the legislation to induce acceptance of recycled products. These developments are prompting researchers to initiate efforts to find suitable applications for many products hitherto considered as waste.

These circumstances also make a strong case for the recycling of non-ferrous slags. A few other reasons that favor this approach and the proposed processing options for these slags are outlined below.

Evidence in the literature demonstrates "pozzolanic" nature of the non-ferrous slag (Réf. 11). A pozzolan, is a commonly used mineral admixture in the modern concrete industry, and is defined as "siliceous material, which in finely divided form and in presence of moisture, reacts with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties". Thus, it is the silica content of the slag that renders pozzolanic properties and converts the slag into a potential binder material. However, consumption of non-ferrous slag as a binder material remains minimal due perhaps to the lack of efforts in promoting such usage.

Other known waste products that have found applications as an admixture in the cement and concrete are - BFS, fly ash and silica fume. Industry initiative combined with several years of research activity and persistent efforts by many researchers have culminated into the acceptance of these three waste products in the construction industry and their consumption has grown consistently over the past decade. (Ref. 12) Figure 1 is prepared to indicate the similarity of non-ferrous slag with these products implying its potential usage in similar applications.

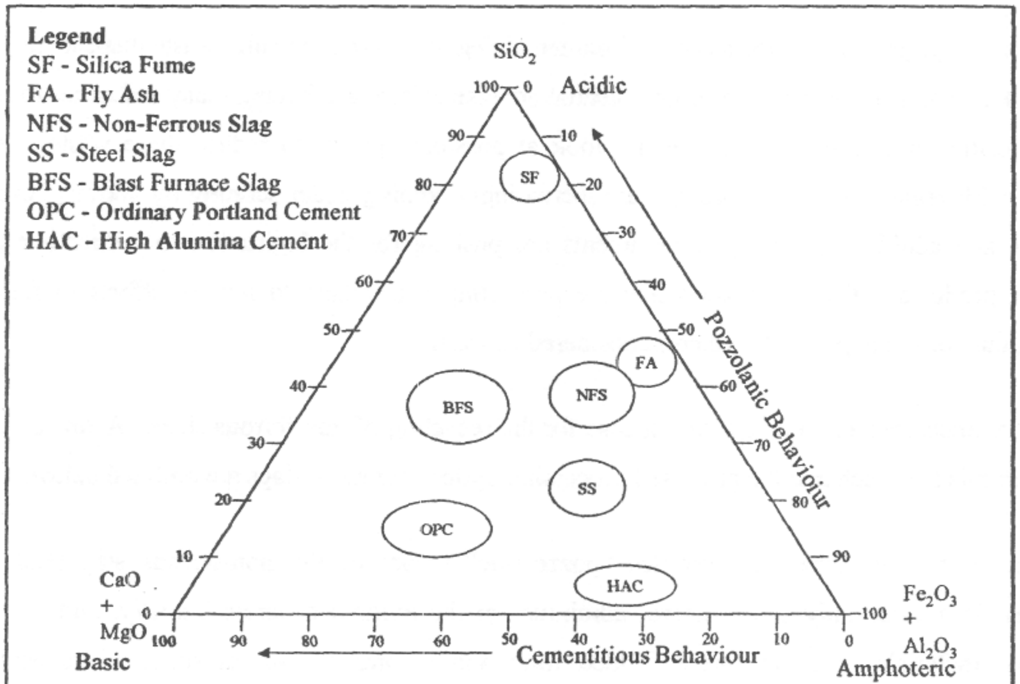

Figure 1. Locations of wastes in the oxide ternary diagram.

The figure shows that the non-ferrous slag can be processed to impart cementitious properties by adding CaO or MgO. Furthermore, it is possible to tailor the slag treatment to improve both the physical as well as chemical characteristics of the slag and make the product suitable for variety of applications.

Table 2 lists the proposed processing alternatives together with the advantages of such treatments and the potential uses of manufactured products.

Table 2. Proposed recycling alternatives for the non-ferrous slags.

Recycling Methodology	Main Advantage/s	Potential Product Uses
Reduction Treatment	• Recovery of metallic values	• Manufacture of slag wool • Lightweight aggregate • Aggregate in embankments
Oxidation Treatment	• Conversion of FeO to magnetite allowing its separation • Impart cementitious properties • Potential metal recovery at lower costs	• Ceramic tiles • Cemented backfill • Clinker ingredient
Combined treatment with otherwaste materials such as steel slag, fly ash and foundry sand	• Addressing environmental concerns with respect to solid waste disposal	• Manufacture of blended cement • Glass manufacture • Concrete aggregate • Filter media
Remelting followed by controlled cooling	• Improve physical characteristics	• Roofing granules • Blasting grit • Aggregate in hot mix asphalt

It should be noted that all the proposed treatments mentioned above are aimed at converting "waste" into a "byproduct".

4. Reclamation Opportunities in British Columbia

During the 6th Industrial Minerals International Congress in 1986, JJ. Emery of Trow Ltd., Ontario, presented a paper titled "Residuals and by-products as construction materials" in which existing and potential applications of several waste materials including slags were described. (Réf. 13) The author, did not emphasize the popular and important topic of environmental improvements, but rather the economic and engineering factors that lead to sound decision with respect to when and how to use the residuals and by-products in construction. In this paper, J. J. Emery has focused on the prevailing situation in Canada with respect to the practices of waste products including non-ferrous slags and concluded that there is much potential for residuals and by-products as materials resources to be developed, and in many cases large stockpiles are available. The situation particularly in regards to non-ferrous slag has worsened since that report about 15 years ago. There is a definite need to reverse this trend for the following reasons.

- Environmental and ecological concerns arising from accumulation of waste deposits.
- Energy and resource conservation.
- Slag represents a source of untapped revenue.
- Slags are a substitute for natural resources such as aggregates and can alleviate shortages;
- Availability of the waste to by-product conversion technology to minimize environmental damage.
- Possibilities of excessive leaching of heavy metals entrained in the slag and its imminent deleterious effects on the environment
- Pressures to reclaim industrial sites.
- Increasing landfill disposal costs.

The above criteria are especially applicable to industrialized provinces such as British Columbia According to Ministry of Energy and Mines there are at least three locations in the province where large quantities of slag are stockpiled. (Ref. 14) Of the three locations, namely - Trail, Anyox and Grand Forks, the Trail is the only location where the: slag stockpile is growing with time as a result of continued smelter operations and therefore an alternative to slag dumping could come as a welcome news. Although the quantity of stockpiled inventory is not available it is estimated that approximately 300,000 to 500,000 tonnes of slag is being accumulated every year. A commitment from management as well as serious efforts by researchers is needed to find additional uses of this waste material. Applications for the slag could be found within a relatively shorter span provided potential end users such as cement industry - support this exercise and the same is encouraged by the governmental agencies.

The slag pile at the Anyox smelter is estimated to contain almost 20 million tonnes of material. The records show that quarrying permit was first issued in 1990 for exploiting the use of the material as an abrasive. By initiating studies one can find out if additional value-added product/s can be manufactured by treating this material. Although the estimate of quantities of slag at the Grand Forks location is not available a research program can be initiated to test the potential applications of this silica rich material.

The proposed recycling program may be extended to other waste materials originating from various Mines and Mineral processing activities. This would allow treatment of tailings waste material such as the one situated about 3 km east of Phoenix mine with an estimated quantity of over 4 million tonnes.

5. Summary

Past producers created large slag dumps that remain unclaimed for as long as 80 years in B.C. with no plans for clean up. In the future, slag producers will be required to reclaim the land where slags are presently stored. All of these factors apply pressure to recycle slag wastes and produce useful saleable by-products. Furthermore concerns regarding the depletion of natural resources and the deterioration of natural environment have given rise to the concept of "sustainable development", the achievement of economic growth while preserving environment for the benefit of future generations. One valid approach to sustainable development is to link industrial operations in networks where one industry's waste becomes another's resource.

The cement industry offers potential opportunity for the development of an industrial ecosystem in this area. A limited research work reported in the literature has supported the possibility of replacing quarried material with wastes such as fly ash and blast furnace slag and further efforts are needed to test inclusion of non-ferrous slag to this list.

Research efforts are needed to find applications for the waste slag as the government regulations are increasingly becoming more stringent with respect to solid waste disposal. By carrying out research targeted at specific slag compositions one can attempt to take advantage of its inherent pozzolanic properties and develop new applications. Additional research could confirm whether cementitious properties can be imparted to the slags and this could pave way for many more applications. All in all there are definite benefits in undertaking slag-related research and follow in the foot steps of iron producers in attempting conversion of a non-ferrous slag from a waste material to a value-added by-product.

List of References

1. R.S. Kalyoncu, 1997, "Slag - Iron and Steel", USGS, Minerals Information, pp. 1-4.
2. V.M. Malhotra, 1987, "Supplementary Cementing Materials for Concrete", A book published by Canadian Government Publishing Centre, pp. 372-377.
3. R.D. Hooton, 1986, "Blended Cements", a book published by ASTM, pp. 15-20.
4. R.H. Mills, 1986, "Blended Cements", a book published by ASTM, pp. 86-89.

5. H.T. Cao, L. Bucea, A. Ray, and S. Yozghatlian, 1997, "The Effect of Cement Composition and pH of Environment on Sulfate Resistance of Portland Cements and Blended Cements", Cement and Concrete Composites, Vol. 19, pp. 161-171.
6. Xincheng Pu, 1999, "Investigation on Pozzolanic Effect of Mineral Additives in Cement and Concrete by Specific Strength Index"', Cement and Concrete Research, Vol. 29, pp. 951-955.
7. Manjit Singh and Mridul Garg, *1999,* "Cementitious Binder from Fly Ash and Other Industrial Wastes", Clement and Concrete Research, Vol. 29, pp. 309-314.
8. W.R.N. Snelgrove and John C. Taylor, 1981, "The Recovery of Values from Non-ferrous Smelter Slags", Canadian Metallurgical Quarterly, Vol. 20, No. 2, pp. 231-240.
9. BIS. terry and C.L. Harris, 1995, "Kinetics of Reduction of Metal Values from Fayalite-based Slags", Transactions of the Institute of Mining and Metallurgy, Vol. 104, pp. C81-C116.
10. C.C. Banks and D.A. Harrison, 1975, "The Recovery of Non-ferrous Metals from Secondary Copper Smelter Discard Slags", Canadian Metallurgical Quarterly, Vol. 14, No. 2, pp. 183-190.
11. F. Hassani jand J. Archibald, 1998, "Mine Backfill", Published by CIM, Canada, pp. 47-55.
12. Vance H. Dodson, 1990, "Concrete Admixtures", Published by VAN NOSTRAND REINHOLD, New York, pp. 159-201.
13. JJ. Emery., 1978, "Residuals and By-products as Construction Materials", Conservation and Recycling, Vol. 2, No. 1, pp. 1-16.
14. Geological Survey Branch of Ministry of Energy arid Mines, 2001, Master Report MINFILE Numbers 082FSW376, 103P 257, and 082ESE264, pp. 1-6.