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PROCESSING OF METALLURGICAL SLAGS AT IRON AND STEEL PLANTS [1]

by

S. Klemantaski,
United Kingdom

[1] The views and opinions expressed in this paper are those of the author and do not necessarily reflect the views of the secretariat of UNIDO. The document is presented as submitted by the author, without re-editing.

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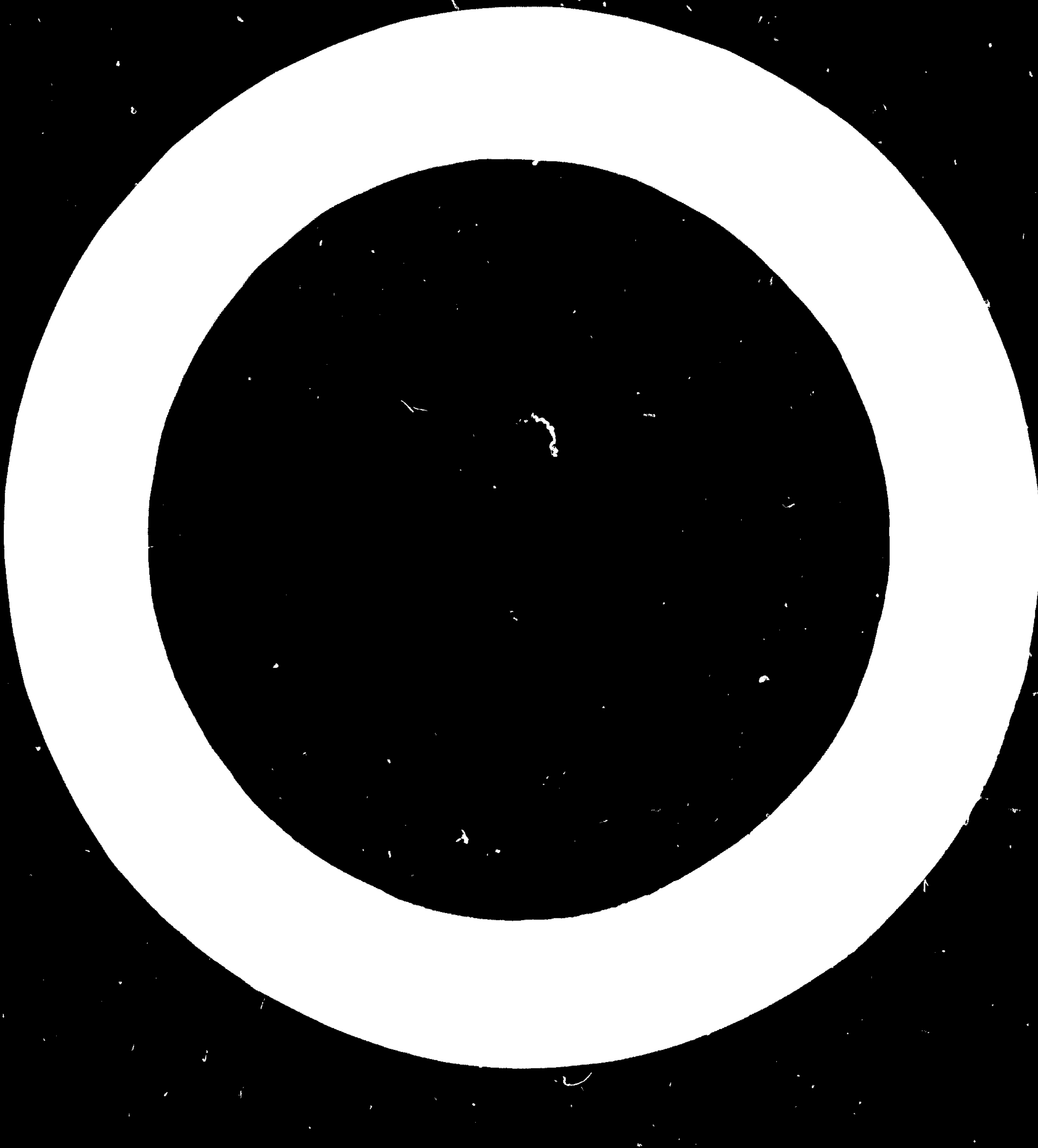

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Processing of metallurgical slags at iron and steel plants[1]

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SUMMARY

Though changes in metallurgical practice are tending to reduce the amount of slag per unit amount of metal, the absolute rate of output of slag is likely to increase because of increasing world iron and steel production.

In most situations slags can, with proper processing and sales policies, become a significant economic advantage. This report considers the main processing methods, the types of slag they suit, the products obtainable and the main quality requirements.

There are two main groups of slags, blast-furnace, and steelmaking. Broadly, it can be taken that steelmaking slags have a considerably higher CaO/SiO_2 ratio and P_2O_5 content than blast-furnace slags.

A. Blast-furnace slags

The main method for processing blast-furnace slags in many countries is to let it cool in the air, the resulting mass being generally crushed and screened and used as an aggregate for concrete, as roadstone, railway ballast and for other purposes. For roadstone the material can be coated with bitumen or tar, the coating being often advantageously made part of the over-all slag processing operation.

* This is a summary of the paper issued under the same title as ID/WG.14/7

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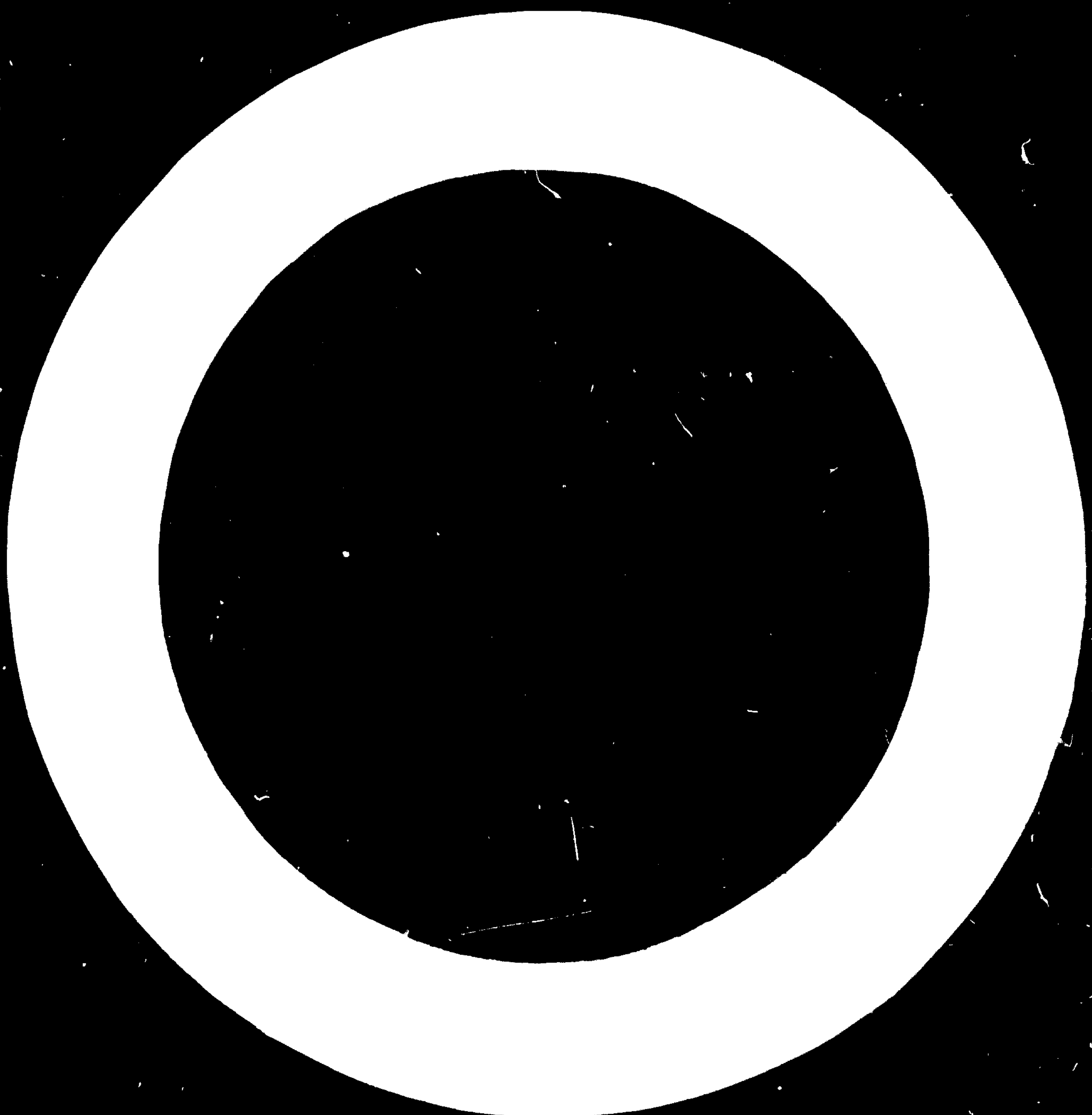

Most applications of air-cooled slag require mechanical strength. This is assessed from the bulk density, which should be above a certain minimum (e.g. 1250 kg/m^3 in the UK standard specification). It is also necessary that the slag should not lose mechanical strength in service (i.e. that the material is not 'unsound'), and this requirement may not be satisfied by slags whose composition (weight %) is such that $CaO + 0.8\ MgO > 1.2\ SiO_2 + 0.4\ Al_2O_3 + 1.75\ S$; that the total sulphur and acid-soluble sulphate (expressed as SO_3) exceed 2.0 and 0.7 wt % respectively; and that the slag cannot survive prolonged water-immersion.

Slags that fail to satisfy strength requirements can find applications by virtue of their chemical composition e.g. as a soil conditioner.

A light-weight, porous material ('expanded slag') can be made by treating the molten slag with a moderate amount of water, or air/water/steam mixtures, sometimes in combination with mechanical action. With a bulk density of 640-1200 kg/m^3 for the fine fraction and 480-880 for the coarse it makes (provided it is not 'unsound') an excellent light-weight aggregate for concrete. Alternatively, under certain processing conditions it can become a good cement.

When treated with a relatively large amount of water (sometimes in combination with mechanical action) molten slags are converted to a sand-like product. If this is finely ground and mixed with an activator (a basic material or sulphate) a good cement results, especially if the composition (weight %) satisfies the formula:

$$\frac{CaO + \frac{1}{2} MgO + CaS + Al_2O_3}{SiO_2 + MnO} > 1.5$$

Molten slag can be spun or blown(or both) into a fibrous material (slag wool) which makes an excellent insulating material. It is used loose, or bonded by stitching or chemically. This relatively high-value application can bear the cost of remelting cold slag.

Slags can be formed directly into useful articles, e.g. kerbstones, by casting. For larger castings a granular filler or steel reinforcements can be incorporated. Better properties can be obtained if the composition of the slag is substantially altered, mainly by addition of silica, in a simple furnace. If a nucleating agent is added at the same time, and the shaped article is heat treated, a form of glass-ceramic of superior properties can be obtained. All these materials are remarkable for their wear resistance, and the glass-ceramic type has many other useful properties.

If the composition of the slag is altered by addition of lime (or limestone) and iron oxide in a special furnace, the melt on cooling gives a clinker of the Portland-cement type.

The handling of slags and slag products forms an important item in their processing costs and adds significantly to the capital costs of a steel industry. Handling methods must be considered an integral part of slag-processing methods. The slags leaving the blast-furnace can be run directly into pits at the furnace or taken away by ladle. In the latter case, the ladles are usually tipped into a pit, but sometimes the slag is allowed to solidify in the ladle.

B. Steelmaking slags

Virtually all steelmaking slags are air-cooled, and their handling is rather similar to that of air-cooled blast-furnace slags.

The 5-10% of metallic iron they contain is usually the most valuable component of steelmaking slags, and its recovery is the main aim of their processing. It is achieved essentially by size reduction and magnetic separation.

In the usual procedure, mechanical crushing and grinding is used, but an alternative is available where the size is reduced through volume increases accompanying deliberately-induced changes in crystalline.

Steelmaking slags from which the metallic iron has been extracted still contain valuable components which can be recovered or made use of if the slags are returned to the ironmaking operation. The slags then behave as a low-grade phosphoric, highly basic, manganiferous iron ore.

Most steelmaking slags can, with little or no processing after iron recovery, be made suitable for use in agriculture either as phosphatic fertilizer (if their soluble P_2O_5 content is high enough) or as a soil conditioner (e.g. as liming agent). A fraction richer in iron oxide and poorer in phosphorus can be obtained from a process for upgrading slags for fertilizer.

Many crushed steelmaking slags are suitable for use as aggregate.

Conclusions

The main conclusions to be drawn from a survey of present slag-processing practice at iron and steel plants and recent developments in this field are as follows:

1) Many methods for processing metallurgical slags at iron and steel plants are available.

2) A slag-processing method can usually be selected to suit a particular slag and particular market situation.

3) Slag processing can often be combined with the convenient removal of slags from the immediate neighbourhood of metallurgical plant.

4) Through processing, slags can be transformed from a waste material with significant handling and disposal costs into profitable by-products such as: aggregate for concrete, coated or uncoated roadstone, filter medium, soil conditioner, phosphatic fertilizer, mineral wool and mineral-wool products, light-weight aggregate and products based on it (e.g. light-weight concrete masonry blocks), cements, cast blocks for foundations, wear-resisting plates.

5) Some slag products are relatively cheap, others command prices that are a significant fraction of the price of the corresponding metal.

6) Recent developments are increasing the scope for slag processing into higher-value products.

7) Some slags contain appreciable quantities of metallic iron whose extraction is a profitable form of slag processing that at the same time forms part of the general scheme for the iron-free slag.

8) Under certain conditions slags have useful metallurgical properties and can be returned to the main process.

9) Special processes can be used to extract valuable non-metallic components from slags.

10) Slag processing should be included in the planning of a steel works, and the possible savings in foreign exchange and capital from the use of slag-based products in the national economy should be kept in mind at the national planning level.

Contents

1. GENERAL INTRODUCTION

With existing methods of making iron and steel each unit of metal is inevitably accompanied by the production of a considerable amount of slag. Changes in practice are tending to reduce this relative amount, but rises in metal production will probably ensure a growing world slag output, though decreases may occur locally.

In most situations, slags can, with proper processing and sales policies, become a significant economic advantage; on the other hand, they can be an expensive nuisance. At some iron and steel works slag-processing and disposal is the responsibility of the works; at some, slag is sold to outside companies as soon as it leaves the furnace; at others, the works sells a partly-processed slag. Each arrangement has its advantages and disadvantages, and the situation must be analyzed for each case (with due regard to possible interference with the operation of the metallurgical plant) to decide which will give the greatest overall advantage.

The economics of slag processing have been discussed recently for limited ranges of conditions*,**. It is impossible to generalize, but the following order-of-magnitude figures may help to provide a frame of reference: (the 'price received' is expressed as percentage of the production cost of a tonne of the corresponding metal).

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* V.I. DOVGOPOL: 'Economics of utilization of metallurgical slags' 1964, 'Metallurgiya', Moscow; Translation No. 4584, 1966 British Iron and Steel Industry Translation service, London.

** Sixième Congrès du Groupe de Travail International des 'Transports Interieurs et Manutentions', 1963, Paris, vol.III.

How slag is disposed of	Price received per tonne of slag
Sold unprocessed	1%
Sold as ungraded aggregate	2%
Sold as graded aggregate	4%
Sold as graded and coated aggregate	10%
Sold as low-quality phosphatic fertilizer	15%
Sold as high quality cement	20%
Sold as high-quality phosphatic fertilizer	30%
Sold after extensive processing e.g. as wear-resisting material	100%
Dumped to waste well away from works	-3% (loss)

One contrast between the economics of iron and steel manufacture and of slag processing is that with slags the materials costs are very low. The cost of the final product is therefore influenced to a much greater relative extent by conversion and transport costs. Another contrast is that slag products often have to compete with naturally available, and often well-distributed, natural materials, that may merely need digging out of the ground. This means that in such applications of slags, little margin is available for processing and transport costs. The situation is different in applications where advantage is taken of the special properties of slags to give a superior product, and in principle it is such applications that should give the greatest overall benefit.

In the early days of slag utilization, the market was restricted not only by economics, but also by lack of confidence in slag products. This has now been largely overcome through the establishment of standards of quality, elimination of incorrect uses, and a vigorous policy of research and publicity.

The present report deals with the processing of the main forms of slag: blast-furnace and steelmaking. Not all the possibilities have been covered, and, in particular, the special processing that can be undertaken on slags from high-alloy steel and ferro-alloy production to extract valuable components has not been dealt with.

2 BLAST-FURNACE SLAGS

2.0 Introduction

The amount of blast-furnace slag produced per tonne of pig iron varies very widely, from over a tonne to less than 1/4. With the trend to the use of richer ores and partial replacement of coke by low-ash fuels, the slag: iron ratio is tending to fall year by year.

Most blast-furnace slags have CaO/SiO_2 ratios in the range 1.0 - 1.2 The other two major components are about 3 - 20% MgO and 30 - 4% Al_2O_3. The minor components are sulphur (1 - 2%) and oxides of iron and manganese (usually in the range 0.2 - 2% each). The molten slags also contain some dissolved gases. Slags leave the blast furnace at temperatures of the order of 1550°C.

The processing of blast-furnace slags is dealt with in the following sections. It can be divided into two broad groups: in one, the slags are allowed to cool in air and then crushed to a stone like material; in the other they are subjected while still molten to various combinations of mechanical action and/or the effects of water, steam and air. In relatively recent developments, processing involves substantial changes in composition and requires heat.

2.1 Air-cooled slags

The main method for processing blast-furnace slags in many countries is to let it cool in the air, the resulting mass being generally crushed and screened and used as an aggregate for concrete, as roadstone, railway ballast and for other purposes. For roadstone the material can be coated with bitumen or tar, the coating being often advantageously made part of the overall slag processing operation.

Most applications of air-cooled slag require it to possess, and retain indefinitely, a certain level of mechanical strength. But even if the slag fails to come up to these requirements, it may under the right conditions still find application by virtue of its chemical composition, e.g. as a soil conditioner for its lime, magnesia, silica, alumina, sulphur or trace-metal contents, or as part of the batch in the manufacture of Portland cement or glass.

The mechanical strength of air-cooled slag is not measured directly, but is assumed to be sufficient if the material is sufficiently free from porosity, which in turn is assumed to be the case if the bulk density is sufficiently high, e.g. at least 1250 kg/m^3 for the conditions given in the British Standard*.

The porosity that air-cooled slags tend to develop is due to the evolution of gas during cooling to form bubbles that do not float out of the slag before it solidifies. One source of bubbles is gas dissolved in the slag; another is sulphur or sulphur dioxide produced by oxidation of sulphide by oxygen (originally atmospheric) carried deep into the molten slag by diffusion iron oxide.

The bulk density of air-cooled slag is, for the usual range of slag compsotions, largely governed by the cooling-process conditions. The process is therefore as far as possible chosen to prevent the bulk density's being too low to enable the slag to be profitably disposed of. To achieve a sufficiently high bulk density additional treatment is sometimes needed. In such cases two procedures have proved effective: addition of iron oxide to the molten slag with steam**. Both inevitably increase costs.

Occasionally, owing to certain of their chemical or mineralogical features, slags are 'unsound', i.e. they lose mechanical strength in service. Three main types of unsoundness are recognized, the best-substantiated being 'lime unsoundness'.

Lime unsoundness is due to the presence in the solid slag of a metastable form of the mineral dicalcium silicate, which is liable to change to the stable form with an 11-% increase in volume. Such a change can cause mechanical failures if it occurs after the slag has been put into service. According to the

* British Standard 1047: 1952, British Standards Institution, London.

** R. EHUNGER, P. MORTIMER & C.N. JOYNT. Submitted for Publication to the Journal of the Iron & Steel Institute.

British Standard* a slag is considered free from lime unsoundness if its composition (in weight percentages) satisfied one or both of the following formulae:

$$CaO + 0.8\,MgO \quad 1.2SiO_2 + 0.4Al_2O_3 + 1.75S \qquad (A)$$

$$CaO \leq 0.9SiO_2 + 0.6Al_2O_3 + 1.75S \qquad (B)$$

There is some evidence** that formula (A) is too cautious for high-MgO slags, and, in any case, failure of a slag to satisfy these formulae does not necessarily mean that it contains the undesirable metastable form of dicalcium silicate. A microscopic test is the only certain way of detecting this form of dicalcium silicate. But is is not certain that even if dicalcium silicate is positively detected the slag is unsound. For example, if there is very little of the mineral, the slag may be able to accommodate the volume increase, or the change may be suppressed altogether. Suppression can be effected by compounds of phosphorous or corrosion (not normally significant components of blast-furnace slag) and in certain circumstances a deliberate addition, e.g. of apatite, may be economically justifiable.

The other two forms of unsoundness are 'sulphur' and 'iron'. The first is avoided if the total sulphur does not exceed 2.0 and the acid-soluble sulphate (expressed as SO_3) 0.7 weight % in a standard test***. Iron unsoundness is unlikely with FeO contents under 1.5% and is considered absent if the slag can be immersed in water under standard conditions without showing signs of failure.

Unassimilated partly-burned flux, which is only present in slags during disturbances in furnace operation, can cause unsoundness owing to volume changes associated with its hydration****. It is therefore best to dump slags made during such periods (which, with improvements in practice, are becoming very rare) or to divert them to uses not requiring sound slag.

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* British Standard 1047:1952, British Standards Institution, London

** A.T. PRINCE: J.Amer. Ceram. Soc., 1954, 37, 402.

*** British Standard 1047:1952, British Standards Institution, London

**** E.W. BAUMAN: Journal of Metals, 1966, January, p 94

Air-cooling processes can be divided into two broad groups: those that need ladles and those that do not.

In the ladle methods the slag from the blast-furnace is run into ladles, which are then left standing long enough for sufficient crust to form on the slag to prevent slopping during transport. In the extreme form of the ladle method the ladles with the mainly liquid slag are taken to sidings, left there until the slag is solid and then taken to a track running along a bank, where the large lumps of slag ('balls') are tipped out and broken before further processing. This method usually gives the highest bulk density. However, it is expensive because it requires a large ladle park and track system.

In the more usual form of the ladle method, the ladles are taken as soon as the crust has formed, and tipped into some form of pit. The pits (or, if it is large enough, different parts of one pit) are filled and excavated in rotation, water spraying or mechanical turning often being provided to accelerate cooling, but only after the slag has solidified.

It has usually been found that the highest bulk density is obtained when the slag can flow into the pit without obstruction (e.g. by ladle skulls) and when the slag forms a thin layer, and the trend is to modify pit practice to achieve this.

Occasionally the slag is tipped down a bank, which is sometimes also used to stock slag from pits before it is further processed.

The method now being increasingly used for air-cooled slags does not need ladles at all, the slag runners leading directly into pits, which are filled and excavated in rotation. The excavated slag is taken by lorry for further processing. The disadvantages of this furnace-pits method are that it gives the least control over slag quality, creates a steam and smell nuisance at the blast furnace and takes up some of the already scarce space near the furnace. On the other hand it is the cheapest, can handle large slag output rates and, as regards the layout and transport system of the works as a whole, provides a simple and flexible method for disposing of slag.

The slag removed from the pit or bank is in a crudely broken-up form. The subsequent processing depends on the use to which it is to be put, but the following is a typical modern arrangement that gives considerable flexibility.

The slag is taken first (preferably after preliminary removal of any large pieces of metal) to a primary crusher, which breaks the slag down sufficiently for efficient removal of metallic iron on the magnetic pulley that follows. The iron, which is the most valuable component of blast-furnace slag, is returned to the ironmaking operation. The slag, now free from metallic iron except in the form of pieces so small that they would not be likely to interfere with further crushing, forms a stockpile. Slag from the stockpile goes to a secondary crusher, through a scalping screen, and thence to a selector screen unit, from which lump slag for uses such as filter media is dispatched. The oversize from the selector screening unit goes to a tertiary crusher through a scalping screen and is returned to the selector screening unit. The undersize from the selector screening unit is screened into fractions which are stored in separate bunkers. There is provision for returning the bunkered material to the tertiary crusher via its scalping screen. Material to be sold uncoated is dispatched direct from the bunkers, generally by road. When coating is required, a batch of the appropriate size blend is dried in a rotary drier, weighed and mixed with the required amount of tar or bitumen dispensed into the mixer from adjacent tanks. The coated material is stored in heated bunkers while awaiting dispatch. The correct ratio of coating material to slag is important if the best results are to be obtained in service without waste of either component.

2.2 Foamed Slag

The tendency of air cooled slag to develop porosity on cooling can be deliberately enhanced. In fact, most blast-furnace slags can be made to foam and then solidify into a porous material, known variously as 'expanded slag', or 'foamed slag' or 'slag pumice'. If made from the right slag under the right conditions it makes an excellent lightweight aggregate.

Usually only a few percent of a country's slag production is foamed, but with the increasing importance of light-weight and insulating building materials, this form of processing is likely to increase.

Foaming can be carried out either directly at the blast-furnace or elsewhere in the steelworks or at an outside site. It is important that the slag temperature for foaming should exceed a certain minimum, but usually the foaming plant can still be far enough away from the blast-furnace for a centralized foaming installation to be possible. A centralized installation has the advantages of a bigger scale of operations and less interference with blast-furnace operation. Some foaming processes are more tolerant than others of cold slag, and this should be taken into account in the choice.

The foamed material is usually crushed and sized as part of the overall process.

Research has still not fully elucidated the mechanism of the foaming process and though some of the factors are becoming apparent, it cannot yet be said with any certainty whether a given slag composition is suitable for foaming under given conditions. It appears that a sufficiently high slag sulphur content and temperature are needed, reducing conditions also being desirable.* But it is often difficult to decide to what extent these are independent variables and can be counter-balanced by changes in temperature and process conditions.

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* W. LAYTON: Proc. Australasian Inst. of Mining & Metallurgy, 1963, March, 57-68

Among process conditions the water used in foaming must be a major factor: it breaks up the mass of molten slag (and probably 'aerates' it) by the expansion due to its evaporation or, in some processes, to a direct mechanical break-up through the mechanical action of water jets, provides the main cooling medium, and may also greatly increase the temperature range in which the viscosity is suitable for foaming.* Fortunately, the suitability of a slag for foaming can usually be decided provisionally from fairly simple practical tests.

As with air-cooled slags, the foamed material must be free from unsoundness if it is to be used where strength is needed. This tends to exclude very limey slags which anyway are liable to give a weak foamed material because of thin inter-pore walls.

The aim of the foaming operation is to produce gas bubbles in the liquid slag under cooling conditions such that the bubbles survive to form pores in the solidified product; the cooling conditions must also prevent excessive fusion together of the individual lumps produced in the foaming operation, since such fusion would complicate handling and crushing.

The main foaming processes can be classified into 'mechanical' in which foaming involves moving machinery; and 'non-mechanical' in which no such machinery is used.

Examples of the 'mechanical' process are those in which the stream of molten slag falls, together with a stream of water, on to a rotating paddle wheel, usually provided with additional water-cooling. Other examples are the foaming conveyor, where slag flows with water via a wheel on to a moving metallic conveyor on which the foaming continues, assisted by a further supply of water in the form of sprays. 'Mechanical' processes have the disadvantages of damage to the moving parts through abrasion, thermal stresses and corrosion.

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* A. FRISAK: Stahl und Eisen, 1923, 43, No. 38, 1219-1228

Corrosion is usually a problem in any slag treatment plant where steam is produced, because the steam is contaminated with sulphur compounds. Since mechanical processes are gradually going out of use, these disadvantages are evidently enough to outweigh the advantages of the additional degree of agitation and independent control they give compared with non-mechanical processes.

One example of the 'non-mechanical' processes is the 'cascade', where the slag from the ladle flows over a series of inclined, overlapping trays covered with thin layers of water. In another non-mechanical process (O.Vorwerk)* molten slag is tipped into a shallow metal bed whose base is provided with jets of water; when foaming has finished the product is removed by tilting the box, which is a considerable handling advantage over an otherwise similar process where the foaming bed is fixed.

A final example is the 'Kinney-Osborne' process in which the stream of slag, usually directly from the blast-furnace slag runner, is broken and partly foamed by a jet of steam or air (sometimes with a little water), and the droplets formed are foamed by fine, air-atomized jets of water. The foamed globules agglomerate to form suitable lumps which are removed by conveyor. This process has the advantage of positive action and a fair degree of independent control of foaming and cooling without the use of moving machinery.**

Good foamed slag should have a bulk density of 640-1200 kg/m^3 for the 0-5 mm fraction (fine aggregate) and 480-880 for the 5-12 mm fraction (coarse aggregate). But low density must be coupled with good strength, and it is in the achieving of this combination that the art of the foaming operation lies. The material should also be relatively light-coloured and, on leaving the plant, should be dry enough for cheap transport and easy mixing.

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* W. RUOPP: Stahl und Eisen, 1957, 77, 36-43

** S.P.KINNEY and F.OSBORNE: Blast Furnace and Steel Plant, 1955, May, 493-501

It is not known to what extent the product from the various foaming processes is crystallized, and a range can probably be obtained from most by changing the conditions. It is claimed, for example, that the Kinney-Osborne process can give a foamed material with hydraulic properties good enough for it to be used in cement making (see 'Granulated Slag'). Foamed slag most probably always contains some glass, however, and this must give the material certain hydraulic properties that would improve the strength of concrete in which it is used as aggregate.

Foamed-slag concretes are used as a bulk material or in pre-fabricated components, e.g. masonry blocks or bricks. As well as lightness, foamed slag contributes good heat and sound insulation. The considerable sulphur removal obtained in foaming is useful if a low-sulphur slag is required, e. g. for glassmaking.

The normal foamed slag has a fairly open-pored structure, which makes for a higher consumption of cement in concretes and correspondingly, a denser and less insulating concrete. A recent development, still experimental*, aims to produce a material with few externally open pores. Enough water is added to molten slag to foam but not freeze it, and the material is passed through two sets of water-cooled rolls. In the first, the smooth rolls form a continuous strip of porous material which the second set of suitable recessed rolls forms into roughly spherical pellets with an almost continuous outer layer.

2.3 Granulated Slag

In some countries, the main method for processing blast-furnace slag at steelworks is by a rapid-cooling procedure known as granulation. The sand-like material produced by this treatment of molten slag can be a useful substitute for sand, but its main attraction is that it can usually be transformed

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* V.I.DOVGOPOL: 'Economics of the Utilization of metallurgical slags', 1964, 'Metallurgiya', Moscow; translated No.4584 1966 British Iron and Steel Industry Translation service, London.

into a cement i.e. it has potential hydraulic properties. For this it is essential that the slag after granulation should be largely in the glassy state, and this is what the rapid cooling is designed to achieve.

To be capable of transformation into cement the slag needs a relatively high lime content. Unfortunately, this requirement is contrary to the other requirement of a mainly glassy material, since high-lime slags tend to crystallize even with very rapid cooling.

The content of other slag components also affects the potential hydraulic properties of a slag granulated under the usual condition and various formulae have been proposed, e.g. (contents in weight %):

$$F = \frac{CaO + \frac{1}{2}MgO + CaS + Al_2O_3}{SiO_2 + MnO} ;$$

the product is very good when F is over 1.9, good when it is between 1.5 and 1.9, and moderate for lower values.*

It is easy enough to test the potential hydraulic properties of a given sample of granulated slag, but since these properties also depend on granulating conditions and, to some extent, on the history of the slag in the liquid state, the results must not be applied uncritically, e.g. in deciding whether a slag of some assumed composition from some planned furnace operation would make a good cement. Some indication of quality is also given by measurement of the proportion of glassy material in the granulated slag, e.g. by observing the colours emitted in ultra-violet light.**

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* F.KEIL: 'Blast-furnace slags' (Hochofen Schlacke) 1963, Verlag Stahleisen, Dusseldorf. p.95.

** W.KRAMER: Chemistry of Cement: National Bureau of Standards Monograph 43, Vol.II, 1962, p.966

There are also certain other limitations on composition imposed by the need for the cement made to remain stable virtually indefinitely, the main one being that the magnesia content of the slag should not exceed about 17%. This limit is intended to ensure the absence of periclase, which can undergo delayed hydration with a 10-% increase in volume. There is evidence that higher magnesia contents may be satisfactory.*

Composition and glass content are less important when the granulated slag is being used in applications such as the filling of marshy ground, where all that is needed is that a reasonable proportion of the particles should become cemented to each other in the course of time, or in soil conditioning, where it is only the solution into the soil of the granulated-slag components that is needed.

Granulating processes are very similar to foaming, but are designed to produce more drastic cooling, generally with the aid of a larger amount of water per unit weight of slag than is used in foaming.

Granulating processes can, again, be classified into 'mechanical' where the process is assisted by moving mechanisms (such as paddle-wheels), and non-mechanical where only flows of fluids are used. But it is also useful to classify them in terms of the moisture content of the granulated slag, since this affects subsequent transport and processing costs, into 'wet', 'semi-dry' and 'dry'.

In 'wet' processes the granulated slag is in effect simply poured into a large excess of water from which it is removed by grab when virtually completely cool. Moisture contents in the granulated slag are then of the order of 25%

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* N.STUTTERHEIM: Chemistry of Cement: National Bureau of Standards Monograph 43, Vol II, 1962, p. 1035-1041

In 'semi-dry' methods, running water and/or high-pressure water jets or sprays are used, and the product may be subjected to partial drying in the course of the process. The moisture content of the final granulated slag is of the order of 10%.

'Dry' methods, of which the Kinney/Osborne process is an example, give an almost dry material, which may often be slightly foamed and is claimed to give superior cements.

As in foaming, the processes can be located at the blast furnace or centrally. Since a lower molten-slag in temperature tends to make it more difficult to obtain granulated slag in the glassy state, the best product is obtained at the furnace; however, this takes up valuable space and creates air pollution problems. To overcome this and at the same time make some use of the sensible heat of the slag for space-heating, a totally-enclosed and compact granulating installation has been developed. This has air-lift movement of the granulate into a raised separating hopper/drier for use at the furnace.* It remains to be seen whether it proves economically viable (corrosion by the wet sulphur-containing gases and by the polluted water is likely to increase costs). In another enclosed installation, the sulphur is washed out of the gases by e.g. caustic soda, and there is provision for generating steam at the expense of the sensible heat of the slag before it is granulated.** Some schemes for utilizing the sensible heat of slags have recently been reviewed.***

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* V.A.USPENSKII and M.A.SHARANOV: 'Metallurgical slags and their use in building' (Metallurgicheskie shlaki i primenenie ikh v stroitel-'stve), 1962, 336-340, Cos.izd.lit, po stroit., arkh. i stroi.mat. Moscow.

** A.Ya.BOLOTIN, L.Yu. ERIKHEMZON, N.K.LEONIDOV and A.V.MARKOV: Stal in English, 1964, (2), 96-98

*** V.D.PASHKOV: Stal in English, 1964, (8), 664-666

For the potential hydraulic properties of granulated slag to be realized, i.e. for it to make a good cement, granulated slag must be ground to a fine powder, and an activator must be present when the powder is wetted for use. The activator must be thoroughly mixed with the granulated-slag powder and can be a strongly basic material such as lime or Portland cement. Since air-cooled or foamed blast-furnace slag is basic, their aggregates are probably especially advantageous in slag cements. Alternatively, for granulated slags whose alumina content is not too low, sulphates such as calcium sulphate can be the activator. Autoclaving is sometimes adopted with lime-activiated slag cements e.g. in the manufacture of slag bricks, but corrosion by the sulphur-contaminated steam can then be a problem.

The amount of activator needed as such is small; larger amounts are used when the activator also contributes something to the properties of the final cement. An example of this is super-sulphated cement, containing at least 75% of granulated slag, calcium sulphate and up to 5% of a basic component. The calcium sulphate contributes to the good resistance of such cements to the action of mildly acid solutions, sea-water and, especially, solutions containing sulphate ions.*

Much granulated blast-furnace slag is used as 'Portland blast-furnace cement', made by grinding the granulated slag with cement clinker, or by mixing the separately-ground materials. The proportion of slag can be high, e.g. up to 65% by weight according to the British Standa[illegible],** provided the magnesia content of the mixture does not exceed about 7% and the sulphuric anhydride and sulphide contents do not exceed about 3 and 1.5% respectively. It appears that higher magnesia contents can be tolerated and the granulated slag

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* J.H.P. VAN AARDT: 'Chemistry of Cement' National Bureau of Standards Monograph 43, Vol II, 1962, p.837

** BRITISH STANDARD 146: 1958, British Standards Institution, London and the other components are advantageously ground separately, so that the optimum size of each can be obtained.*

Slag cements in general have low heats of hydration, which makes them eminently suitable for large masses, such as dams. The fact that they are made by the blending of at least two components and that the components can be ground separately makes it possible to modify the properties of slag cements considerably, e.g. their setting time.

2.4 Slag Wool

In most countries only a fraction of a percent of the total output of blast-furnace slag is used for slag wool production. This is not because slag wool is not competitive, but because the tonnage demand for mineral wool in general is low. However, the potential is considerable** and the manufacture if slag wool and products based on it can be profitable and should not be neglected in the planning of a steel industry.

The slag for wool production must not be very basic, a CaO/SiO_2 ratio of 1.2 being about the maximum. However, the relatively high value of slag wool makes modification of composition feasible.

Slag wool is produced from molten slag, usually obtained by remelting lump slag in cupola-type furnaces. This operation is expensive in manpower and fuel, requiring about one part of metallurgical coke for three parts of slag. Remelting can, however, be carried out without coke in reverberatory or electric-arc furnaces, which have the further advantage of being able to melt slag shot; this can be important, since the conversion of molten slag to slag wool by most processes produces slag shot as an unwanted by-product, often in large amounts, and if the slag has borne a significant

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* N.STUTTERHEIM: J.Am.Concrete Inst., 1960, 31, No.10, 1027-45

** For conditions in the U.K. the approximate amount of mineral wool for the insulation of one house is about half a ton.

transport cost the inability to use it fully could represent a serious loss.

A more rational solution to slag-wool production is to use slag that has remained molten, and a suitable installation has been described.* This is based on direct oil-firing, with a very simple furnace having an upper opening to receive molten slag from the ladle and a lower opening for the discharge of the slag to the wool-making machine.

In this furnace the heat needed is, for the most part, merely that for keeping the slag temperature at the right level and, possibly, for melting the minor additions sometimes made. The capital cost of such an installation has been given as about 1/7th of that based on a cupola, and manpower as 1/5th.

The molten slag, however produced, is transformed into fine fibres by a process that can be of one of the following broad types:

a) Pure jet. The slag stream, or each stream produced by its subdivision, is acted upon by jets of steam or air, which blow the slag into fibres while it is still in the viscous state and cool the fibres formed so that they do not weld together on contact.

Recent developments of this type of process subdivide the slag to a high degree by passing it through fine orifices before it is acted upon by the jets.

b) Combined. The stream is first formed by a rapidly rotating wheel into a ring of molten slag, which is then blown by steam or air jets; the preliminary forming makes the blowing more effective.

c) Mechanical. The molten slag is pulled into fibres by the action of rotors of various types, without the action of jets; some compressed air is still needed, but only to remove the fibres already formed.

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* L.V.BRODETSKII: Metallurg, 1957, (12), 36.

Pure-jet processes (but not the fine-orifice variants) are mechanically simple but tend to have a low productivity and to give a high proportion of shot in the product. Since shot cannot be remelted in a cupola, it is better not to use such furnaces with pure-jet processes. The orifice developments of pure-jet processes are claimed to give low shot contents, but against this, one must remember that orifice wear is likely to be a problem.

The other methods (and one of the fine-orifice variants) have the usual disadvantages of moving parts under hot and dusty service conditions, but have relatively high productivities with good product quality, although the single-rotor mechanical process tends to give thick fibres.

For good slag wool the fibres must be fine (a few microns thick), long (70mm would suit most applications) and interlaced, and must have enough strength to resist stresses during further processing and the service conditions of the final product. The bulk density for the main applications, i.e. thermal and sound insulation, should be about 110 kg/m^3. The wool can be used loose, or formed into products, such as insulating blankets with the wool bonded mechanically by stitching, or acoustic tiles, in which a chemical bond is used.

Where chemically bonded products that require heat for curing are being made (which would be the case for the widely used resin bonding), the availability of waste heat from the wool-making process would make it better to site the two operations close together, which would at the same time avoid the difficulties of transporting a material as bulky as unformed slag wool.

At present, slag-wool manufacture tends to be a small-scale operation, with outputs per installation of a few tonnes per hour. This makes it difficult to achieve low production costs or to justify the provision of the high degree of process control needed for achieving a consistently high quality of product. The situation is no doubt partly due to market factors, but the possibilities for large-scale, integrated manufacture of slag wool and its products should not be neglected.

2.5 Shaped articles of blast-furnace slag.

In the processing methods so far considered, the blast-furnace slag is broken down into granular, powder or fibrous materials that are either used as loose aggregate or are recombined with the aid of some binding material, such as cement, or form a cement themselves. However, provided they are sound, blast-furnace slags can be shaped (mainly by casting) directly into components such as kerbstones, pipe-lining plates or large blocks. So far this has been a relatively small-scale outlet for slag - of the order of tens of tonnes per day per plant.

One of the difficulties is the expense of the long annealing time that is normally needed to avoid the cracking of even small cast-slag parts, another is the low productivity of slag-casting installations. For example, on an installation where 30 tonnes per day of blocks 200 x 100 x 100 mm. in size and about 6 kg in mass were cast into an array of 120 cast-iron moulds arranged around the periphery of a slowly-turning horizontal wheel, about a two-hours' annealing followed by slow cooling was needed, and the blocks were loaded into the Dutch ovens and unloaded by hand. However, experiments* with roll-type forming machines give promise of much higher productivities and lower labour requirements.

The tendency of blast-furnace slag castings to form cracks during cooling increases with increasing size of casting, and probably also depends on the casting temperature, mineralogical composition, crystal size uniformity, content of uncrystallized

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* V.I.DOVGOPOL: 'Economics of the utilization of metallurgical slags', 1964, 'Metallurgiya', Moscow, p.55. Translation No.4584, 1966, British Iron and Steel Industry Translation Service, London.

material and porosity and the attainment of conditions to give the right combination of these factors should enable improvements to be made. It has, furthermore, been reported* that if a granular filler is placed in the mould before the molten slag is admitted, much greater cooling rates can be achieved, the castings being removed from the mould at a temperature of about 900°C and allowed to cool in the air. Moreover, any cracks that form during early cooling are apparently confined to the surface and heal up.

Probably the most advanced development of slag casting is to incorporate steel reinforcements**. This would make cracking less of a danger, but, in addition, the greater contraction of the steel during cooling produces a certain degree of advantageous pre-stressing of the component, and steel-reinforced castings of blast-furnace slag could probably be used for important duties such as foundation blocks. This would represent a considerable extension of slag-processing opportunities for steelworks. A difficulty is that the high teperature to which the steel is raised by the molten slag causes some deterioration in the mechanical properties of the steel, and further research is clearly needed.

With their good compressive strength and resistance to aggressive waters, cast-slag products are suitable for use as tunnel and mine-shaft linings, and because of their high wear resistence they make good linings for bunkers, chutes and pipes handling abrasive materials such as coke or sinter. An important disadvantage of cast-slag products in all these applications is that the castings have to be relatively thick and this means that the lining takes up a significant part of the cross-sectional area.

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* G.F.TOBOL'SKIKH: 'Metallurgical slags and their use in building' (Metallurgicheskie shlaki i primenenie ikh v stroitel'stv),1962 Cos.izd.lit. po stroit., arkh. i stroi. mat., Moscow, pp 363-368

** N.A.KARTASHOV: 'Metallurgical slags and their use in building' (Metallurgicheskie shlaki i primenenie ikh v stroitel'stve),1962 Cos.izd.lit.po stroit., arkh i stroi. mat., Moscow, pp.352-363

2.6 **Shaped articles of blast-furnace slags of substantially modified composition.**

Mainly because of the shortness of the temperature range in which they remain liquid, blast-furnace slags of the normal composition have poor casting properties. This shortness is due mainly to their relatively high lime content, and casting properties can be greatly improved by increasing the silica content. This, especially when combined with other changes in composition, can at the same time give a better crystal structure with improved properties of the casting.

In one installation designed for the casting of blast-furnace slags of modified composition,* molten slag from the blast-furnace ladle is charged via a tundish into a regenerative rotary furnace, where 25 parts of silica sand and about 40 parts of clay are added to every 100 of slag. There is also some enrichment of the melt with magnesia and chromium oxide from the refractories. The melt is cast into sand or metal moulds; the castings crystallize and are annealed and slowly cooled.

The properties of the castings are considerably better than of those from ordinary blast-furnace slags, but the addition of 65 parts of cold material to the slag and its assimilation is expensive.

In another approach, which needs considerably less addition of cold materials, the blast-furnace slag is in effect transformed into articles of what may be considered a crude form of glass-ceramic.

For this, the slag composition is changed in two main ways. One, designed to ensure that the melt forms a stable glass on cooling, consists in the addition of about 30 parts of silica to every 100 of slag.

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* 'Production and use of slag castings' (Proizvodstvo i primenenie shlakovogo lit'ya), 1963, Goskomitet po chernoi i tsvetnoi metallurgii pri Gosplane SSSR, Upravlenie gornodobyvayushchei promyshlennosti.

The other, designed to cause evenly-distributed nuceli to develop in the slag glass when it is heat treated after solidification, is achieved by the addition to the melt of a few percent of nucleating agent, which may consist of one (or a combination of several) of a fairly wide range of materials, including fluorides and transition-metal oxides. Other changes in the composition of the melt are sometimes made, e.g. of soda to improve the shaping properties of the slag glass; such additions may be important technologically but do not affect the principle of the method.

Though it is possible, and may be more convenient, to base the process on the remelting of solid slag, it is more rational to use slag that is already molten. This saves not only fuel but also capital costs for the first stage of the process, the production of a melt of the required composition. This stage, which can be carried out in any convenient furnace, produces a glass that in the next stage is shaped, e.g. by casting, pressing or rolling, modified to take account of the steep temperature dependence of the viscosity of such glasses. In the third stage, the shaped product is heat treated, first by being held at about its annealing temperature to allow the nuclei to develop, and then at a higher temperature to allow crystals to grow on the nuclei. The heat treatment gives a material of relatively fine and uniform crystal size with a small amount of residual glass. Changes in process conditions can give a range of colours, and enamelling is also possible and cheap.

The material is remarkable for its very high resistance to wear, and this, coupled with the fact that it can be obtained thin, makes it an excellent liner for bunkers, chutes, pipes etc. handling abrasive material.

It is also hard and strong (though rather brittle) and has good reistance to alkaline media, sea water and polluted atmospheres. These properties, together with the attractive appearance it can have, make it a promising building material and a potentially outstandingly profitable by-product of the steel industry. Work in this direction has been reported in the USSR ('slag sitalls')*, Poland**, Hungary***, and the UK ('slagceram')****.

In the UK, commercial production of wear-resistant articles has started. The status in other countries is not known, but a series of products including corrugated sheet, foamed and unfoamed panels, and composite panels of foamed and unfoamed material, pipes and insulators, have been listed in a Russian publication.*****

Without heat treatment or without the nucleating agent a dark, opaque glass is obtained from the silica-enriched melt. Although this might have some decorative value, its properties are greatly inferior to those of the glass-ceramic type material.

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* I.I.KITAIGORODSKII: Zh.Vses.Khim. Obshchestva im D.I. Mendeleeva, 1963, 8, (2) 192-7.

** B.ZIEMBA and E. CHLOPICKA: Szklo i Ceramika, 1965, 16, 69-71

*** B.LOCSEI: Acta. Chim. Hung., 1960, 22, 1.

**** S.KLEMANTASKI and B.KERRISON: Chemistry and Industry, 1966, Oct.15. 1745-1755

***** Encyclopaedia of modern techniques; constructional materials, Vol.3 II, pp. 196-171, 1965 (Ed. A.T.Tumanov)

2.7 Fused cement clinker.

In the previous section, the composition of the blast-furnace slag was modified in the direction of a higher silica content. If, on the contrary, additions are made to increase the lime content with a simultaneous increase in iron oxide, a melt whose composition is similar to that of Portland cement can be obtained. Because of the high temperatures needed, this is a difficult operation but at least two methods have been reported.

In one, originally developed by Wennerstrom* the additions to the slag are introduced in an arc furnace. Considerable improvements have recently been made, notably the use of lime rather than limestone and a magnesite instead of a graphite lining.** In the other method, developed by V.V.Serov, a 'converter' supplied with liquid fuel and pre-heated oxygen-enriched air is used.**, ***. The lime-rich melt tapped from the converter is granulated, which gives a better cement than obtainable with relatively slow cooling. The economic advantages for conditions in the USSR of this process, which has been tried on an industrial-experimental scale and could yield by-product steam for electricity generation have been disputed,****.

Since the melt can presumably be granulated to give at least some glass, the cement made from it may well have properties superior to those of ordinary clinker-based cement.

2.8 Handling and transport of blast-furnace slags

The handling of slags and slag products forms an important item in their processing costs and add significantly to the capital costs of a steel industry. Improvements in

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* K.G.WENNERSTROM: Tek. Tidskrift, 1926, Almanna Adelingen, N24, (224)

** I.I.KHOLIN and S.M.ROYAK: 'Chemistry of Cement', National Bureau of Standards. Monograph 43, Vol II, 1962, p.1063-1065

*** V.F.KRYLOV and V.K.POMYAN: Tsement, 1960, No.2, 1-7

**** A.GUDIMOV: Ekonomicheskaya Gazeta; 1963, No.3 (76) Jan.19,41-42 handling methods to reduce costs and capital costs must therefore be considered an integral part of the slag processing methods. These aspects have been recently reviewed* and will only be briefly touched on here.

Where slag ladles are used, the recently developed 'swinging spout' method which enables a single blast-furnace runner to deal with as many ladles as necessary is worth noting**. So far, the principal method of transporting ladles has been by rail. The cheapest form of ladle is tipped by a rope pulled by the locomotive while the ladle wheels are locked. In the other common form the ladle is tipped by compressed air. Rail transport is relatively inflexible, but specially designed road vehicles with tipping arrangements have become available***, which, being suitable in addition for the transport of molten metal and other hot materials, would have considerable advantage as regards the internal transport arrangements of the steelworks as a whole.

Whether slag ladles are used or not, the solidified slag must be reclaimed. Machines for ripping and dozing**** are available for air-cooled slags powerful enough to enable drilling and blasting to be avoided even on very old, highly compacted slag banks. Large hard lumps from banks are generally broken by a steel ball. For loading the reclaimed air-cooled slag, wheel loaders are increasingly taking the place of excavators, which have the disadvantage of slow movement between sites. For furnace pits it would be advantageous to have remote-controlled equipment capable of working at high temperatures, as the faster reclamation would enable pit areas to be reduced for a given slag output rate.

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* Sixieme Congres du Groupe de Travail International des 'Transports Interieurs et Manutentions', 1963, Paris, vol III, see especially the paper by M. Wilkinson

** V.I.KRIVENKO, G.B.RABINOVICH, V.D.SERGIENKO and D.A.STOROZHIK: Stal in English, 1964, (10), 772

*** Steel Times, 1966, November 18, 668-670

**** Steel Times, 1965, October 1, 436 - 437

Where close control of the slag pouring rate is needed, ladles with tapholes may be preferable. However, they involve more manpower, and therefore systems for the automatic tipping of ladles to give constant slag flows have been devised in recent years.*

The finely-divided products from foaming and granulation can be piped considerable distances with water to dewatering stockpiles well outside the plant area. The disadvantages of this form of transport is that the increased moisture of the material may be difficult to remove (this is especially true of the porous foamed material), and the relatively high wear of the pipes owing to the very abrasive nature of slag pulps, which would make a lining desirable.

3 STEELMAKING SLAGS

3.0 Introduction

The situation with steelmaking slags is much more complicated than with blast-furnace slags: there are many different steelmaking processes, and each can, in the course of normal operation, produce slags of very different compositions. For example, the slag leaving a basic open-hearth furnace at one stage contains 14% CaO and 26% SiO_2, and at another 46% CaO and 18% SiO_2. However, in terms of the weighted mean composition, the great majority of steelmaking slags have CaO/SiO_2 ratios of about 2 and over, and it is with them that the present report is mainly concerned. They usually contain metallic iron and oxides of iron and other metals. Their phosphorus content covers a very wide range (about 1 - 25% P_2O_5) the trend being to lower values, and their sulphur content is usually a few tenths of a percent or less. In addition, fluorides are sometimes added to increase fluidity.

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* Yu.A. LUKOVSKII, L.Yu. ERIKHEMZON, Ya. P.GINDIS and P.N.AKININ: Stal in English, 1961, (7), 476 - 478

The following sections consider the handling of steelmaking slags, and their processing to a) recover metallic iron, b) make use of their chemical properties by returning them to the metallurgical cycle and, c) render them suitable for external disposal.

It will be seen that the processing of steelmaking slags is much less varied than that of blast furnace slags, being largely confined to the solid state and made up of size reduction, screening and magnetic separation. There are no significant counterparts to the liquid-state processes that blast-furnace slags, with their higher SiO_2 content are amenable to.

3.1 Handling of steelmaking slags

Virtually all steelmaking slags are air-cooled, and their handling is rather similar to that of air-cooled blast-furnace slags.*

Some steelmaking slag is run into pits either from the furnace itself or as overflow from the steel-pouring ladle. The excavation of these pits often has to be done quickly because of high production rates and lack of space, and under difficult conditions (congestion, heat, steam and fumes from water sprays) and is preferably helped by powerful remote-controlled equipment.**

Where slag ladles are used, lack of headroom sometimes makes it necessary to remove them from their rail carriages for filling and then replace them. This involves extra handling costs but gives some additional flexibility to traffic near the furnaces.

The ladle carriages may be drawn as a train by locomotives, or they may be self-propelled, the latter being increasingly favoured.

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* Sixième Congres du Groupe de Travail International des 'Transports Interieurs et Manutentions', 1963, Paris, vol. III: see especially the paper by M.Wilkinson.

** 'Making, Shaping and Treating of Steel', 1964, Eighth Edition, United States Steel, 488, 490

The disposal area is usually a pit, but when slag solidifies in the ladle the mass is tipped out on to a bank.

3.2 Iron recovery

The 5 - 10% of metallic iron they contain is usually the most valuable component of steelmaking slags, and its recovery is the main aim of their processing. It is achieved essentially by size reduction and magnetic separation.

The iron-recovery procedure can vary, but the following is a common form.

The molten slag is tipped from the ladles into one of at least two pits, one of which is being filled while the other is excavated. Before excavation starts, the solidified slag is sprayed with water, which cools the mass and breaks it up to some extent.

A mobile crane then repeatedly drops a very heavy iron ball on to the slag, and periodically moves a magnet over the broken slag to extract lumps of metal, and the remaining material is then excavated. Any solid slag from the steelmaking plant is now added. The large lumps are screened out and the finer material is passed through magnetic separators. The magnetic fraction from the separators and the large lumps from the screen are then charged into one end of a long perforated rotating barrel. The tumbling action frees the large pieces of iron from adhering slag and they leave the discharge end sufficiently clean to be returned direct to the steelmaking plant. The rest of the material falls through the perforations and is taken for further magnetic processing.

An alternative iron-recovery procedure reported* is based on the disintegration of the steelmaking slag not by mechanical

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* V.I.DOVGOPOL: 'Economics of Utilization and Metallurgical Slags. Steelmaking slags'. 1966 British Iron and Steel Industry Translation Service, No.4584

action but through the unsoundness to which most basic slag compositions incline them. In this procedure, a few percent of finely divided dicalcium silicate (e.g. in the form of slag that has already undergone the treatment) is added to the molten slag flowing into the ladle. The added material provides nuclei for the crystallisation of dicalcium silicate in the slag, most of which then disintegrates during the latter stages of cooling to give a product ready for magnetic separation and screening; recovery of metallic iron is high and the non-metallic products are ready for several uses.

This procedure is not suitable for slags of high phosphorus content, or for slags of basicities of less than 2. For such, addition of limestone into the slag ladle can induce disintegration, but the product needs some mechanical crushing.

3.3 Return of steelmaking slags to the metallurgical process.

Steelmaking slags from which the metallic iron has been extracted still contain valuable components which can be recovered or made use of if the slags are returned to the ironmaking operation.

In the blast furnace the relatively high lime content of steelmaking slags can be used (possibly at the cost of some additional coke) to flux the acid components of the gangue and coke ash. The iron and manganese present as oxides in the steelmaking slag are largely recovered in the pig iron. This is advantageous, but the effect with phosphorus, which is also recovered in the pig iron, is not so clear-cut. It is advantageous, for example, if high-phosphorus foundry irons are required, or if, as might sometimes be the case, the market for high-phosphorus steelmaking slag is sufficient to justify the expense of this recirculation method of concentration to produce P_2O_5 enriched batches. Otherwise, phosphorus in the blast-furnace burden is a disadvantage, and this, or the presence of other undesirable components, may prevent the re-use of steelmaking slags.

When steelmaking slags are in a very finely divided state it may be possible to use a highly-selective magnetic separation to divide the slag into a magnetic fraction richer in lime and iron oxide and a non-magnetic fraction richer in phosphorus and silica. The magnetic fraction makes a better input material to the ironmaking operation, but must be sintered; the non-magnetic fraction makes an improved basic slag phosphatic fertilizer*.

3.4 Processing of steelmaking slags for other uses

Most steelmaking slags can, with simple processing after iron recovery, be made suitable for use in agriculture, and in civil engineering as aggregate (if free from lime unsoundness) and as a cement.

There are two extremes of the agricultural uses of steelmaking slags. In one they act as phosphatic fertilizers. This requires a relatively high total phosphorus content (lower limits of as high as 16% P_2O_5 are set in some countries) most of which must be soluble in 2% citric acid solution, and a finely-divided state. The need for high phosphorus content restricts such use to slags from the refining of high-phosphorus pig iron. The magnetic-concentration procedure described in 3.3.2 can widen the range to lower P_2O_5 contents and since a fine state division is needed in any case, may well prove economical. The solubility requirement restricts fertilizer use further to slag relatively free from fluoride. Fine grinding is the principal processing needed for this use of slag, but for greater convenience in handling some re-agglomeration of the fine particles without impairment of their reactivity is desirable, and addition of other materials to improve their agricultural value is also possible.

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* G.G.BROWN and K.F.J.THATCHER: The Fertilizer Society, London, 1967, Proceedings No. 96

The other extreme of agricultural use is for soil conditioning, e.g. as a liming agent. The finer slag materials from the iron-recovery operation can be used without further processing. It is one of the advantages of most steelmaking slags that they function as both fertilizers and soil conditioners. The trace-element content of slags can be valuable in agriculture.

The stabilizing effect of the phosphorus content of many steelmaking slags makes the coarser fractions from the iron-recovery operation suitable for use as aggregate etc. even though their compositions lie in the 'lime unsoundness' range.

Most steelmaking slags if finely ground make useful low-grade cements. The fine material from the dicalcium-silicate method (3.2.2) is ready for use in this way.

4. GENERAL CONCLUSIONS

The main conclusions to be drawn from a survey of present slag-processing practice at iron and steel plants and recent developments inthis field are as follows:

1) Many methods for processing metallurigical slags at iron and steel plants are available.

2) A slag-processing method can usually be selected to suit a particular slag and particular market situation.

3) Slag processing can often be combined with the convenient removal of slags from the immediate neighbourhood of metallurigical plant.

4) Through processing, slags can be transformed from a waste material with significant handling and disposal costs into profitable by-products such as: aggregate for concrete, coated or uncoated roadstone, filter medium, soil conditioner, phosphatic fertilizer, mineral wool and mineral products, light-weight aggregate and products based on it (e.g. light-weight concrete masonry blocks), cements, cast blocks for foundations, wear-resisting plates.

5) Some slag products are relatively cheap, others command prices that are a significant fraction of the price of the corresponding metal.

6) Recent developments are increasing the scope for slag processing into higher-value products.

7) Some slags contain appreciable quantities of metallic iron whose extraction is a profitable form of slag processing that at the same time forms part of the general scheme for the iron-free slag.

8) Under certain conditions slags have useful metallurgical properties and can be returned to the main process.

9) Special processes can be used to extract valuable non-metallic components from slags.

10) Slag processing should be included in the planning of a steel works, and the possible savings in foreign exchange and capital from the use of slag-based products in the national economy should be kept in mind at the national planning level.

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