ABSTRACT

Dry separation techniques for the beneficiation of primary and secondary raw materials are gaining increasing interest throughout the world as the use of water is often costly, not appropriate due to technical reasons and product specifications, or water is simply not available.

An integrated technical solution for the recycling of steel slag is presented. The goal of the system is to optimize metal recovery on the one hand by a combination of new dry processing methods, but not neglecting the applicability of the residual slag on the other hand. The concept comprises the slag handling steps:

- Selective slag comminution
- Separation by sensor-sorting and density methods
- Re-use of the liberated and de-metalized slag as by-product for the construction industry considering high value and ecological applications.

Based on proper slag processing, possible slag applications that are not completely implemented in the actual state of the art for slag processing/handling are introduced. The implementation of this integrated concept in the industry requires a joint effort by steel makers, processing specialists and construction aggregate application and marketing departments.

Keywords: Steel slag, dry processing, density separation, aggregate application, slag processing

1. INTRODUCTION

In Germany, roughly 750 Mt of minerals per year are used as construction aggregates. Approximately 86% of the demand is covered by natural aggregates (such as sand and gravel or crushed stone). The residual amount consequently is coming from secondary sources (mainly demolition waste).
This article deals with the processing and application of slag from steel making. In Germany, the biggest portion of the 9 Mt of blast furnace slag is processed to slag cement. The residual amount of BF slag plus roughly 6 Mio of slag from low alloyed steel production and 1 Mt of slag from high alloyed/stainless steel production are used as aggregates in different construction applications. Approximately 2 Mt of steel slags are still dumped on landfills.

It should be mentioned that “application as construction aggregate” covers a wide range. This includes high quality uses e.g. in asphalt top layers with strict specifications as well as low-value shaping applications for covering landfills (mostly for stainless steel slags).

As slag is coming from high temperature processes in constant qualities and low in fluctuation of chemical compositions it should be a by-product for which applications of high value can be found individually for different slag types.

A concept for an optimized application mix for different steel slag types is presented in this paper. A pre-condition allowing those applications is a new processing concept containing new - especially dry - metal recovery methods and already starting with the slag handling and cooling process. The present article mainly focuses on application for high alloyed or stainless steel slags as for them high value applications are often restricted by contained heavy metal grades.

### 2. SPECIAL SLAG PROPERTIES WITH RELEVANCE FOR CONSTRUCTION APPLICATIONS

In this chapter, special properties of steel slags affecting their applicability in construction are introduced.

Table 1 shows typical chemical compositions of different slag types generated during steel making compared with some other materials used in the aggregate and binder industry.

<table>
<thead>
<tr>
<th>Component</th>
<th>EAF, low alloyed</th>
<th>EAF, high alloyed</th>
<th>Sec. metall. slag</th>
<th>Blast furnace slag</th>
<th>Natural Puzzolan</th>
<th>Fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>30-45</td>
<td>50-60</td>
<td>55-60</td>
<td>35-46</td>
<td>2-9</td>
<td>1.5-8</td>
</tr>
<tr>
<td>MgO</td>
<td>3-8</td>
<td>5-9</td>
<td>4.5-10</td>
<td>1-12</td>
<td>1-3</td>
<td>1.5-4</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3-7</td>
<td>1.5-5</td>
<td>1.5-10</td>
<td>7-14</td>
<td>15-21</td>
<td>24-30</td>
</tr>
<tr>
<td>FeO/Fe₂O₃</td>
<td>6-10</td>
<td>1.5-6.0</td>
<td>1.0-1.5</td>
<td>0.2-2.4</td>
<td>5-8</td>
<td>5-15</td>
</tr>
<tr>
<td>Fe, met.</td>
<td>2-5</td>
<td>2-4</td>
<td>3-5.5</td>
<td>+/-1</td>
<td>0-1</td>
<td>0-1</td>
</tr>
<tr>
<td>Basicity¹)</td>
<td>2.1</td>
<td>2.4</td>
<td>2.6</td>
<td>1.2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Extended Basicity²)</td>
<td>2.4</td>
<td>2.8</td>
<td>3.0</td>
<td>1.4</td>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>Other metal oxides</td>
<td>1 – 2</td>
<td>5</td>
<td>3.5 - 0.8</td>
<td>0.5</td>
<td>&lt;1.5</td>
<td>&lt;1.5</td>
</tr>
</tbody>
</table>

¹) CaO:SiO₂²) (CaO+MgO):SiO₂
It is known that the higher the basicity, the higher is the probability of volume instability of the material, with negative effects on the construction application. Furthermore, free CaO and MgO negatively affect volume stability.

Regulations on maximum swelling values (depending on the application, less than 1, 2.5 or 5%, resp.[1]) in some cases prevent slags - especially from secondary metallurgy – from being applicable in those uses. Volume stability can be positively influenced by certain measurements already during slag handling. That includes treatment such as rapid cooling and addition of additives (chemicals, sand, etc.) of/to the liquid slag.[2][3][4][5] If such an treatment is not an option, slag can be stored for a certain period to react with humidity and reach volume stability.

Blast furnace slag is well known to develop hydraulic behaviour upon quick quenching and fine grinding, making it utilizable as so-called slag cement. According to recent publications also other slag types, e.g. EAF slag, can be modified in a way to develop a hydraulic behaviour after grinding. Therefore, it seems to be possible to replace a certain percentage of traditional binder by slag.[7][8] Hydraulic behaviour (and also slag properties) is influenced by slag temperature, slag composition, slag viscosity, granulation conditions, glassy proportion and fineness. It is also state of the art to influence the chemical slag composition already in the blast furnace or at least immediately after decanting.[6]

Ecologically, especially stainless steel slag sometimes is critical with regards to leaching of heavy metal ions, such as Ni, Cr and Mo, and regulations prevent the application due to limit values concerning leaching or solid matter contents. If heavy metal grades can not be reduced by processing, it has to be examined if the slag can be used in bounded concrete or asphalt applications to immobilize contained heavy metals.

### 3. NEW SLAG PROCESSING AND APPLICATION CONCEPT

#### 3.1 State of the art in slag processing

There are two basic approaches of processing steel slag (and all options in between and/or mixing options 1 and 2):

- Metal separation by hand picking, magnets and selective crushing after sizing to -45 mm or alternatively
- Fine grinding of the complete slag to a size -0.1 mm and recovery of the metal by hydraulic and/or screen classification.

Approach 1 limits the separation of metal to a size of +45 mm. The remaining 0/45 mm fraction is typically used as aggregate in road construction and filling/dumping material. To increase value, the slag might be classified into aggregate fractions 0/4, 4/8 and so on. Capital and operating cost for such techniques are low. But taking into account that typically 50% of the metal contained in the slag is finer than 10 mm, a large portion of the metal is lost. Furthermore, the risk of high heavy metal leaching from the slag increases.
Therefore, especially for slags from high alloyed steel making containing high grades of Cr, Ni, Mo and others, it has become state of the art to apply wet fine grinding. The typical process comprises crushing and two-step fine grinding (rod mill/ball mill). As the ductile metal is not ground, it can be separated from the mineral part of the slag by screening or classifying. The resulting fineness of the mineral part of the slag is typically >95% below 0.2 mm. This process recovers more than 95% of the metal and produces metal concentrates grading at 90 to 92% of metal. With regards to metal separation it can be regarded as nearly optimum process. [17]

The main disadvantage is that the complete by-product is fine slimes and the according material composition makes it difficult to use in construction as long as it is wet. Therefore, large portions of that material are only dumped, which – in many parts of the world – is often related to high cost and to legal restrictions. Any higher value applications make it necessary to treat the wet slag slimes one way or another (drying, agglomeration,…)

To summarize: Usually it has to be chosen between high metal recovery OR advantageous applicability of the residual slag. Typically, the decision between those options is made depending on the value of the contained metal.

3.2 A new approach to slag processing

The process presented in this paper aims at significantly increasing metal recovery compared to approach No. 1, but at the same time optimising the values of application for the various slag products. Compared to state-of-the-art concepts, it comprises the following innovations or innovative combination of known processes:

Liquid slag modification (optional)

Double tilting and slag granulation (optional)

DRY pre-concentration for all size fractions

Fine grinding only of pre-concentrates

Issues 1 and 2 aim at the production of high quality slag products, such as slag with cementitious behaviour and at increasing volume stability. But even if those issues are not taken into account, the residual concept of dry pre-concentration compared to wet processing has several advantages.

Advantages by pre-concentration and grinding of pre-concentrates only:

- Crushing and grinding limited to pre-concentrates (Energy and wear savings)
- Lower generation of fines
- Metal-free aggregate can be used in high quality construction applications
- Metal recovery down to 0.1 mm possible from pre-concentrates

Advantages by dry processing:

- Redundancy of costly water cycle
- Dry products (especially for the fines which can be applied as filler)
- Applicability of dust from de-dusting as filler
- If above mentioned issues 1 and 2 are taken into account: maintaining hydraulic/puzzolanic properties of the slag during processing
3.3 **Processing technology**

Summarized roughly the new process comprises the following steps:

- Separate treatment of slag from primary and secondary metallurgy
- Pre-concentration and separation of metal carrying fractions by dry separation methods such as:
  - Sensor systems (Induction, X-Ray, LIBS)
  - Magnetic separators (LIMS/MIMS)
  - Density separation by air jiggging and
  - Dry fluidized bed separation (fine fraction)
- Crushing of oversize metal free aggregate and screening to required aggregate fractions (e.g. 0/2, 2/8, 8/16; 16/22; 22/45; or others)
- Crushing of metal pre-concentrates minus 25 mm, recovering metal +25 mm
- Separation by density method (minus 25 mm) and for any pre-concentrate dry grinding to achieve a filler product which has a controlled fineness of approx. 4000 Blaine.
- NOTE: In case water has been used for slag cooling the remaining water in the slag should be re-moved by drying as soon as possible (Use of mechanical rapid driers). Free-flowing material is necessary in order to have good separation conditions. Therefore the fraction 0–4 mm should be dried.

To have an efficiently working dry pre-concentration process for all relevant size fractions it is essential to implement recent technology.

Depending on the type of metal to be recovered, magnetic separation, hand picking and especially sensor based sorting can be applied for pre-concentration from the coarse fractions +25 mm. With those processes it is possible to recover up to 90% of the metal or even more. From the pre-concentrates metal can be upgraded by selective comminution – if the metal products are not pure enough.

For 4/20 mm, sensor sorting partly is too costly due to limited capacity. Magnetic separation with different magnets (LIMS/MIMS, up to ca. 0.8 – 1.0 T) is an option, if the contained metal is magnetic and the mineral part of the slag is non-magnetic or only to a limited extend. For this fraction, air jigs have proved to work efficiently on a density separation basis. In recent years, German company allmineral developed a new air jig with an automatic process control system and implemented it to numerous for coal and iron ore separation [16]. With this equipment, metal recoveries of +80% can be achieved depending on the degree of intergrowth of the slag.

Until recently, there was a gap in dry processing for the slag fines -4 mm (making up roughly 50% of the total slag!). If magnetic separation is not an option, because the metal is non-magnetic, or the slag itself is responsive to magnetic separation, there is need for gravity separation equipment. Apart from several types of air tables, which for mineral applications
usually are limited with regard to capacity, there was no industrial equipment for fine dry gravity separation applicable to metal separation from slag. To close that gap, German company CALA Aufbereitungstechnik developed a fluidized bed separator that at high capacities efficiently recovers a large portion of contained metal to a low amount of pre-concentrate. As this is a new development more details are presented in the next sub-chapter.

### 3.4 CDF Separator for dry density separation of fines minus 2 (4) mm

The fluidized bed separator (CDF separator) was initially developed to process heavy mineral deposits in aride climate areas, where water supply is a problem. Mineral sands carry Titanium minerals, Monazite, Zircon, Anatase and others, all typically having a density of +4.5 t/m³ compared to 2.7 t/m³ of gangue minerals. As this separation in many cases works efficiently, it is obvious that it also works with slag processing because even higher differences between slag and metal occur.

Figure 1 shows the working principle of the CDF Separator. It makes use of a fluidized bed to layer components according to their density.

![Figure 1. Schematic drawing and picture of a fluidized bed separator, Type CALA](image)

The material is fed on the one end of the separation area on a screen deck. This screen deck is driven by two unbalanced motors. A constant air flow is generated and blown into the material layer from under the screen deck and this way fluidizing it. 3 rotary star gates discharge the bottom layer regulated depending on the adjusted velocity. With these heavies discharges, 3 different products can be produced separately. At the end of the separation area the upper layer of material is discharged as light product to the overflow. The whole machine is sealed and dust is collected on top of the dust hood.

The capacity of the machine varies between 10 and 25t/h per meter working width and depends on the bulk density of the feed material. It is possible to process particles in a range of 0.1 to 4 mm and the heavies mass recovery is selectable nearly without limitation.
Exemplary results of tests with stainless steel slag can be summarized as follows.

A slag fraction 0.1-3 mm containing roughly 5% of metal was fed to the machine at 20 t/(h x m). The separation task was to find out the performance of the system producing final concentrates. Figure 2 shows microscopic pictures of heavy product 1 (metal) and the lights product (clean slag). Table 2 summarizes the sorting efficiency.

![Figure 2. Products from dry separation of SS-slag by CDF-Separator](image)

<table>
<thead>
<tr>
<th>Product</th>
<th>Mass distribution [%]</th>
<th>Metal grade [%]</th>
<th>Metal recovery [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>100</td>
<td>5.3</td>
<td>100</td>
</tr>
<tr>
<td>Heavies 1</td>
<td>3</td>
<td>98</td>
<td>55.5</td>
</tr>
<tr>
<td>Heavies 2</td>
<td>2</td>
<td>87</td>
<td>32.8</td>
</tr>
<tr>
<td>Heavies 3 (Middlings)</td>
<td>10</td>
<td>4</td>
<td>7.5</td>
</tr>
<tr>
<td>Lights</td>
<td>85</td>
<td>0.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Heavy product discharge 1+2 produced a concentrate containing more than 90% of metal at a recovery of 88%. Losses of metal in the overflow product are limited to 3% at a mass pull of metal-free slag of 85%. The product from middlings discharge 3 can be either put to stream „pre-concentrate” to increase recovery to 97%, or it is added to the overflow, in case the system is producing final concentrate, or as 3rd option it is recycled to the feed of the CDF.

### 3.5 Application mix for steel slag

The quantitative composition of the high quality product mix is depending on the nature of the raw slag with regards to initial size distribution, metal size distribution, liberation of metal and slag and so on. It has to be optimized for each slag individually.

One potential product mix is compiled in table 3. This mixture has been developed on products from processing tests on stainless steel slag.
Table 3. Exemplary product mix from dry processing

<table>
<thead>
<tr>
<th>Fines from first stage of dust separation system (mostly from sec. slags):</th>
<th>23%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil conditioner, Replacement of lime for soil stabilization</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aggregate for asphalt and/or concrete:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand replacement (0/4 mm)</td>
<td>24%</td>
</tr>
<tr>
<td>Coarse aggregate replacements (4/100 mm; classified)</td>
<td>28%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filler for manufacturing self compacting concrete und mastic asphalt:</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal recovery from slag</td>
<td>5%</td>
</tr>
</tbody>
</table>

There is an ongoing investigation about re-agglomeration of fines after metal separation following the system as presented by Sawada (#12). He is mixing up binder, filler, sand and Portland cement with water in order to re-build aggregate by pelletizing the material and crushing it to needed sizes after curing for a certain period.

The main disadvantage of that system is the high cost of Portland cement. The mentioned ongoing investigations by the authors are dealing with new ways of cooling the slag in order to create hydraulic behaviour in the slag. Under these conditions the Portland could be replaced by Filler type II and thus make the system even more economical.

5. **ECONOMICAL APPROACH AND OUTLOOK**

Please compare the 3 alternative processes hereafter in detail:

Table 4. Key figures for the alternative treatment of steel slag by different separation methods

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Dry separation with magnets, hand picking &amp; selective crushing</th>
<th>Wet separation with jaw crusher, rod/ball mill and complete water circuit</th>
<th>Dry separation with jaw crusher, multiple pre-concentration by sensor and density</th>
</tr>
</thead>
<tbody>
<tr>
<td>...at a yearly tonnage of 150 000 t slag</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment (Mio. €)</td>
<td>1.5</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Inst. electr. power (kW)</td>
<td>850</td>
<td>2100</td>
<td>1200</td>
</tr>
<tr>
<td>Metal recovery (t/a)</td>
<td>5 850</td>
<td>8 500</td>
<td>8 000</td>
</tr>
<tr>
<td>Value of metal (1000 €/t)</td>
<td>5.85 Mio. €</td>
<td>8.5 Mio. €</td>
<td>8.0 Mio. €</td>
</tr>
<tr>
<td>Earnings by marketing of slag fractions</td>
<td>./</td>
<td>./</td>
<td>2 – 16 €/t, i.a. ca. 9 €/t = 1.27 Mio. €/a</td>
</tr>
<tr>
<td>Disposal fees for slag products</td>
<td>0 – 6 €/t, im Mittel ca. 3 €/t = 0.43 Mio. €/a</td>
<td>6 – 15 €/t, im Mittel ca. 10 €/t = 1.41 Mio. €/t</td>
<td>./</td>
</tr>
</tbody>
</table>
Total annual revenue  | 5.42 Mio. €/a  | 7.09 Mio. €/a  | 9.27 Mio. €/a  
---|---|---|---
...less operating costs  
Oil/Gas  | ./. | ./. | 2.0 Mio. €/a  
Electricity  | 1.21 Mio. €/a | 3.0 Mio. €/a | 1.8 Mio. €/a  
Water/flocculants  | ./. | 0.4 Mio. €/a | ./.  
Personnel/other operating costs  | 6 €/t = 0.9 Mio. €/a | 9 €/t = 1.35 Mio. €/a | 8 €/t = 1.5 Mio. €/a  
Spare parts  | 0.08 Mio. €/a | 0.2 Mio. €/a | 0.18 Mio. €/a  
Capital costs (6% & 10 years)  | 0.24 Mio. €/a | 0.64 Mio. €/a | 0.56 Mio. €/a  
Total operating costs  | 2.43 Mio. €/a | 5.59 Mio. €/a | 6.04 Mio. €/a  
Gross Profit p. Year  | 2.99 Mio. €/a | 1.50 Mio. €/a | 3.23 Mio. €/a  
Gross Profit (€/t slag)  | 19.93 €/t | 15.0 €/t | 21.53 €/t  

The future tendency is rapidly increasing prices for disposal and restrictions by governmental Authorities that high value application must be found. Thus dry separation at high recoveries is the only solution for consistent and sustainable slag processing techniques which finally will also be the only economical approach.

REFERENCES


[17] US005427607A patent: Process for the recovery of metallic iron from slags and other residues