POSSIBILITIES TO IMPROVE THE MECHANICAL AND PHYSICAL PROPERTIES OF SLAG FOR ITS SECONDARY UTILIZATION

ZEGZULKA Jiří [1,2], BOTULA Jiří [3], JEZERSKÁ Lucie [2], KRATOCHVÍL Michal [3], HLOSTA Jakub [2], NEČAS Jan [1,2]

[1]VSB - Technical University of Ostrava, Faculty of Mechanical Engineering, Institute of Transportation, Ostrava, Czech Republic, EU
[2]VSB - Technical University of Ostrava, ENET Centre, Laboratory of Bulk Materials, Ostrava, Czech Republic, EU
[3]VSB - Technical University of Ostrava, Faculty of Mining and Geology, Institute of Mining Engineering and Safety, Ostrava, Czech Republic, EU
jiri.zegzulka@vsb.cz, jiri.botula@vsb.cz

Abstract

The aim of the study was to investigate the possibility of a partial upgrade of the existing technological line at the company *Calumite s.r.o.*, intended for the treatment of blast furnace slag for its secondary use. The first step was detailed characterization of the materials by means of mechanical-physical parameters, among which are, for example, the particle size distribution, compressibility, and the angle of internal and external friction. In the next step, the method of magnetic separation was used to reduce the content of magnetic components in the samples, due to the potential of slag to also be used in the production of clear glass, among other types of use. Subsequently, it was examined how the original mechanical-physical characteristics of the measured samples have changed.

The results suggest that the added magnetic separation operations allow us to declare the *Fe* content in the non-magnetic parts of the product below the 0.1% limit. There was; however, slightly less effective separation of the material. After the above-mentioned material treatment, we succeeded in both cases in reducing the wall friction and increasing compressibility of the product, whereas the angle of internal friction and flow-ability remained with unchanged modes. Therefore, in terms of economic considerations, the introduction of an additional operation with magnetic separation for the treatment of blast furnace slag on the technological line can be assessed as a suitable innovation, and the secondary product can be used for the production of clear glass.

Keywords: Slag, calumite, magnetic separation, internal and external angle, compressibility

1. INTRODUCTION

Almost every operational activity is currently accompanied by the production of smaller or larger quantities of waste. This issue is addressed by waste management legislation within the EU, which emphasis reducing waste, reuse of generated waste, or its removal by applying only such methods that would not endanger human health or the environment. Secondary sources should gradually replace primary raw materials. However, this activity can be carried out only in places where it is technically possible and economically effective. As a result, we can help to reduce the material and energy intensity of production. These are basic alternatives that save natural resources and contribute significantly to environmental protection. Unfortunately there are often hazardous or toxic wastes that may pose a significant environmental hazard [1, 2, 3].

Businesses and companies that are faced with hazardous wastes try to eliminate hazardous substances using various technological processes or reusing the materials further within the production cycle. Metallurgy, as an industry engaged in the processing of ores and in metals production, is among the biggest polluters. In metallurgical operations there arise every year over 100 different types of industrial wastes, most of which fall into the category of hazardous wastes. The composition of these wastes can vary and depends on the method and time of sampling in terms of the campaign stage of the plant, the phase of the technological cycle, the type of processed raw material, and on other factors [1, 4, 5]. Higher fees for landfill and waste collection should motivate firms and companies to reduce dumping waste, which still would become radically more expensive over the coming years (the Law on Waste being prepared foresees an increase in the fees for each tonne of waste delivered to landfill). According to the plan of the Ministry of the Environment, it will motivate businesses to recycle and incinerate waste on a larger scale. Law No. *185/2001* Coll. on waste and amending certain other laws, specifically in Annex 1 (Classes of Waste), in section Q8 - Residues from Industrial Processes, states that blast furnace slag is a hazardous waste; this study deals with this type of waste. The aim of the study is to show how slag, a hazardous waste, can be used as a raw material for further processing. An example is given in an existing technology, and there are other options shown as to how it can be innovated [3, 6, 7]. Among the current methods of using blast furnace slag waste are for example civil engineering, glass industry and production of mineral fibres [2].

2. MATERIALS, EXPERIMENTS, AND METHODS

Several kinds of blast furnace slag were used in the study (**Fig. 1**). After determining their basic mechanical and physical properties to examine the possibility of further use in a particular technology, only two samples were tested, which were interconnected technologically - *Calumite®* Slag and slag from *ArcelorMittal a.s.*

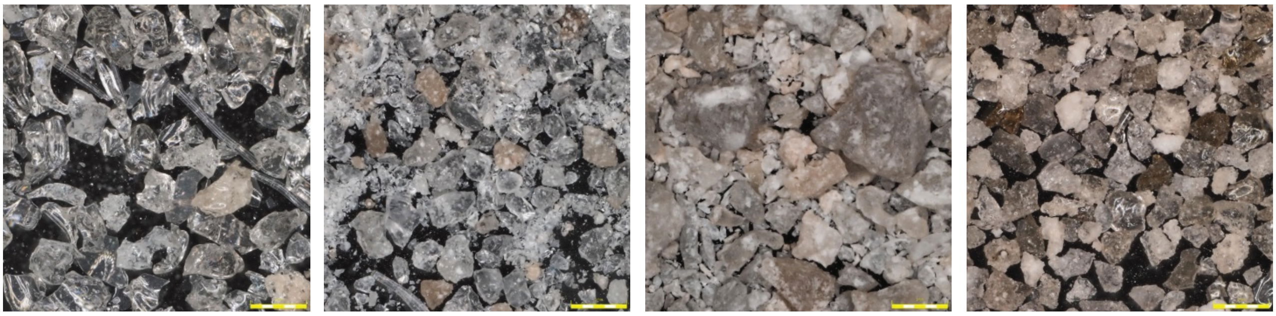

Fig. 1 Blast furnace slag from various suppliers. ARM - *ArcelorMittal Ostrava a.s.*, CAL - *Calumite®* Ostrava, UKR - *Ukraine (Krivoy Rog)*, IND - *India (Maharashtra)*

2.1. Sieve analysis

A sieve analysis was performed according to standard ČSN EN 933-1 (721193). This standard conforms to European Standard EN 933-1:2012. We used Part 1: Determination of Particle Size, Sieve Analysis (content: *5 Test equipment; 6 Preparation of test samples for analysis; 7 Test procedure; 8 Calculation and expression of results)* [8].

2.2. Angle of internal friction, wall friction and compressibility

The device used for bulk properties measurement was an FT4 Powder Rheometer [9].

Angle of internal friction: The rotary shear module for measuring friction parameters consists of a vessel containing the sample powder and a shear head to cause normal and shear stress. The blades of the shear head sink into the mass powder and the front face of the head starts to apply normal stress to the surface of the powder bed. The shear head moves downwards until sufficient and stable pressure is applied between the head and the powder bed. Then the shear head starts to rotate slowly and thus cause shear stress within the bulk mass. The shear plane is formed just below the end of the blades. Since the powder bed prevents rotation of the shear head, shear stress in the measuring plane increases until a slippage occurs. Then, the maximum value of transferred shear stress is recorded.

Wall friction angle: The rotary shear module for the measurement of wall friction angle is similar to the case of measuring the angle of internal friction. The stainless steel contact surface of the shear head descends onto a powder sample, and the front surface of the head begins to introduce normal stress at a stable condition on the surface. Then shear stress is induced, which is incremented until a slippage occurs.

Compressibility: Compressibility is measured as the change in volume or density, respectively, depending on a normal load. The data obtained are quantified by expressing the percentage compressibility for a normal load of 15 kPa applied by the module, which is part of the FT4 powder rheometer.

2.3. Magnetic separation

Magnetic separation is used for the concentration of magnetic materials and for the removal of magnetizable particles from fluid streams. The separation is achieved by passing the suspensions or the mixtures of particles through a non-homogeneous magnetic field.

This process leads to preferential retention or deflection of the magnetizable particles. The same objective is often achieved in a very different fashion, the common features being a competition between a wide spectrum of forces of various magnitudes and ranges.

In magnetic separation the separating (differentiating) external force is the magnetic force. The separation of one material from another or the removal of magnetizable particles from streams depend upon their motion in response to the magnetic force and to other competing external forces, namely gravitational, inertial, hydrodynamic and centrifugal forces [10].

3. RESULTS AND DISCUSSION

From the results of the sieve analysis shown in **Fig. 2** it applies that the slag material from the company *ArcelorMittal a.s.* is coarser than the other tested samples.

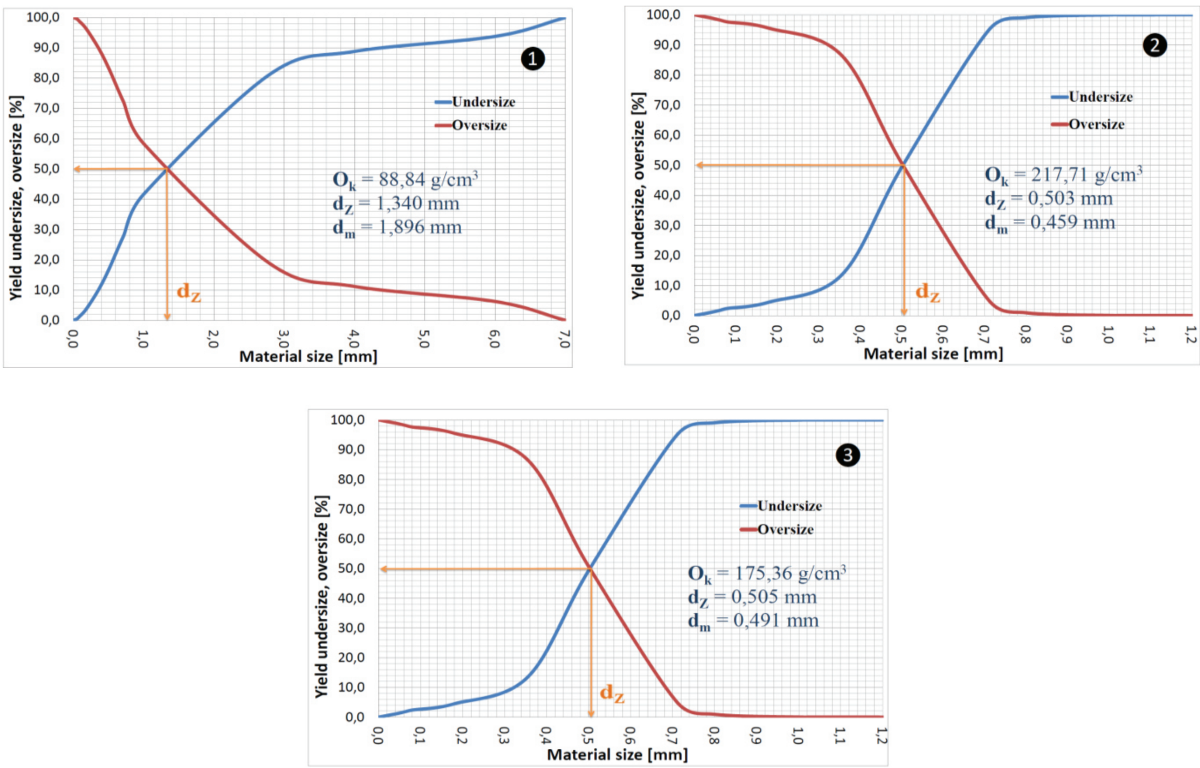

Fig. 2 Results of the experiment - Granulometric Analysis (❶ ArcelorMittal, ❷ Calumite, ❸ India)

Note: O_k - value of specific surface area; d_Z - grain size parameter; d_m - size parameter of the particle mean diameter

This is also related to the value parameter of the specific surface area, which is the smallest in slag from *ArcelorMittal a.s.* (*88.84 g/cm*^{3}). This is caused by the wide range of material sizes and moreover by the occurrence of large components in the sample. The slag material from India and slag from the company *Calumite s.r.o.* have a very similar granulometry. The only difference was found in the value of the specific surface area when the slag from the company *Calumite s.r.o.* has a greater value (*217.71 g/cm*^{3}). The value of the specific surface area slag form India is *175.36 g/cm*^{3}.

The company *Calumite s.r.o.*, in cooperation with *VSB-TU Ostrava*, examined the treatment possibilities of the *Calumite*© product by magnetic separation to reduce the content of *Fe* from the average value of 0.15% to a value below 0.1% of *Fe* content. Then the material could be used for white and transparent glass, which is very sensitive to the *Fe* content in the input batch. This innovation would extend the portfolio that the company could offer to the market. A laboratory experiment which simulated this option - magnetic separation - was carried out on a magnetic separator with permanent magnets and magnetic induction of *0.84 T,* from *MEZ Mohelnice*, type: AP71-1 (year of manufacture: 1965). The company dealt with this idea already in the past when increasing the performance of the magnetic separator which was already present in the manufacturing process. But this resulted only in the removal of a large amount of slag that could normally be further used. Therefore, the company *Calumite s.r.o.* is now interested in innovating the process line in another way so as to allow separation of the slag part containing less than 0.1 % of *Fe.* The resulting values of the described laboratory experiment are shown in **Table 1**.

Table 1 Results of experiment - magnetic separation of slag *Calumite*© and *ArcelorMittal a.s.*

Product	*Calumite*©			*ArcelorMittal a.s.*		
	Return	Content Fe	Yield Fe	Return	Content Fe	Yield Fe
	[%]	[%]	[%]	[%]	[%]	[%]
Concentrate (NMP)	38.56	0.0815	20.45	36.52	0.1298	23.92
Waste (MP)	61.44	0.1989	79.55	63.48	0.2375	76.08
feed	*100.00*	*0.1536*	*100.0*	*100.00*	*0.1981*	*100.0*
Note: NMP (Non - Magnetic Product); MP (Magnetic Product)						

The results indicate that the *Fe* content in the sample of *Calumite*® slag fell below 0.1 %. This NMP product is therefore suitable for the production of white and clear glass. Technologically untreated *ArcelorMittal a.s.* slag showed a content of 0.1298 % of iron after its magnetic separation. The fact is closely related to the number of steps (mag. separation) on the production line.

For non-magnetic and magnetic products, we measured their mechanical-physical parameters such as the angle of internal friction, wall friction angle and compressibility to detect changes in the mentioned properties due to magnetic separation of samples, i.e., the change in the composition by removing *Fe* from the *Calumite*® sample as far as below 0.1 %. Shear properties are important, for example, in determining the degree of difficulty in putting a consolidated material into motion. In order to make a slag powder flow (e.g., transport of material, storage, vaulting), it is necessary to overcome the yield strength of the material. This property is affected by the physical characteristics of the material, including its shape, size, particle surface, and the content of moisture or other additives. It is obvious from the resulting data (**Table 2**) that the parameters which are affected by magnetic separation the most are compressibility and the wall friction angle; this is more marked in slag from *ArcelorMittal a.s.* Wall friction after magnetic separation decreases to about 37 %, which indicates easier movement of loose slag along a contact material. Conversely, the angle of internal friction is, in both cases, nearly the same. This phenomenon implies the fact that the angle of internal friction is not dependent on *Fe* content in the sample.

Table 2 Mechanical and physical properties of slag samples before and after magnetic separation

Material - Slag	***ArcelorMittal***	***ArcelorMittal after MS***	***Calumite***	***Calumite after MS***	***India***
Angle of Internal Friction, [°]	44.5	44.8	41.4	40.1	46.7
Flowability, -	Easy-flowing material				
Wall friction angle, [°]	18.80	11.80	26.10	23.00	25.30
Compressibility (15 kPa), [%]	3.36	6.76	2.76	3.11	2.13
Bulk density, [g.cm^{-3}]	1.27	2.19	1.62	1.96	1.21

Compressibility is a measure of volume changes or density, respectively, depending on the normal load. Generally, cohesive powders are more compressible, unlike raw bulk materials with coarser granulometry. It is clear from the data that compressibility rose after magnetic separation in both cases, up to twice in the *ArcelorMittal a.s.* sample. After the magnetic separation, the material would become easier compactable, can be rolled easier or shaped otherwise. This difference is not very significant in the *Calumite®* slag. This is mainly due to the fact that the *Calumite®* slag has already undergone several treatments in the preceding technological process - i.e., it is a final product.

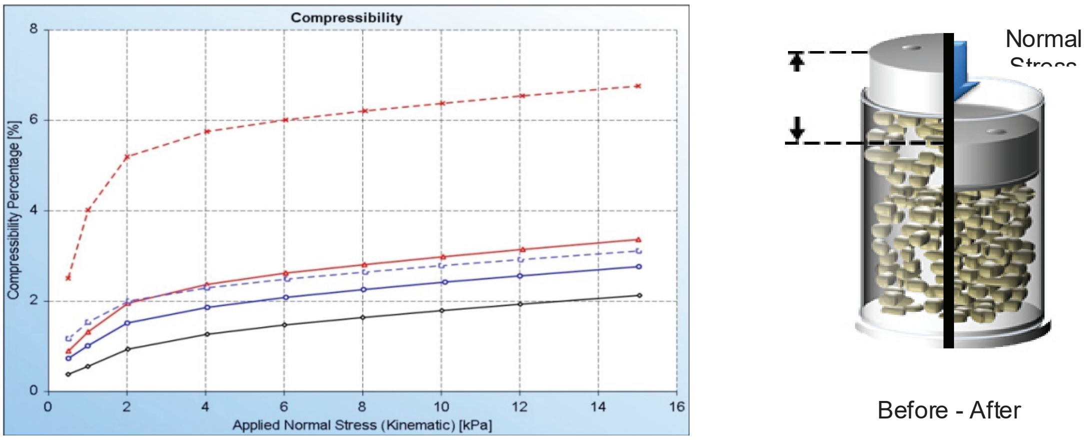

Fig. 3 Changes in the compressibility of slag samples before (full line) and after (dashed line) magnetic separation (---- *India*, ---- *Calumite®*, --- *ArcelorMittal a.s.*)

4. CONCLUSIONS

Magnetic separation of two samples of slag - *Calumite®* and *ArcelorMittal a.s.* - led not only to a change in content of magnetic components, but also to a change in the mechanical and physical parameters of the samples. Both cases proved a decrease in the value of the wall friction angle due to the additional process of magnetic separation. This leads to a reduction in frictional forces between the slag and powder material with which it may be in contact. After magnetic separation, the slag features a reduction in energy intensity in terms of the flow of the bulk material being tested, for example, through a discharge chute. Reduced *Fe* content affected the wall friction angle values more than the angle of internal friction values. With the change in the composition, hardly any values of angle of internal friction changed. Compressibility values in the samples after treatment by magnetic separation had a growing character. The material can be compacted, rolled, or shaped otherwise to a greater extent.

It is evident from the results that the additional process of magnetic separation could be incorporated into the existing technological line, which would then enable disassociation of the raw material into magnetic and non-magnetic parts. In this respect; however, it would probably be necessary to increase the "in-process" controls of the product, especially for the non-magnetic part of the product used for the production of clear glass. However, for the introduction of the above-mentioned innovation, it is necessary to prepare an economic balance of the company and to collect more data by additional measuring.

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