Energy effective approach for activation of metallurgical slag

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Abstract. The paper presents results of investigation of the process of mechanical activation of metallurgical slag using different approaches – ball milling and electromagnetic vortex apparatus. Particle size distribution and structure of mechanically activated slag samples were investigated, as well as energetic parameters of the activation process. It was shown that electromagnetic vortex activation is more energy effective and allows to produce microscale milled slag-based concrete using very short treatment time. Activated slag materials can be used as clinker-free cement in civilian and road construction, providing ecology-friendly technology and recycling of high-tonnage industrial waste.

1. Introduction
Technological wastes of metallurgical industry are produced in significant amount every year. Slag output during production of ferrous metals results in increasing yearly per ca. 5-7 M tons, providing high environmental load and waste of nature.

One of the promising ways of utilization of metallurgical slag is its use as a component for construction materials, such as clinker-free concrete. Note that nowadays there are few technologies allowing energy effective use of metallurgical slag in the building industry. Most of approaches use slag for production of gravel, as filler for concrete and road pavements etc. [1,2]. Mining and separation of rare-earth metal produces various slags, which can be recycled for additional extraction of rare metals and used for production of construction materials.

Energy effective utilization of metallurgical slag with subsequent production of construction materials for civil and road applications is of great importance and needs usage of special mechanical activation technologies with low energy consumption and high efficiency. This paper presents preliminary results in the development of energy effective and cheap approach to production nanoscale-milled materials basing of blast-furnace slag as a model industrial raw material. The same approach can be used for activation of other slags, produced during rare earth extraction and processing.

2. Experimental
The process of formation of clinker-free cement materials was investigated using blast furnace slag produced by Joint Stock Company Severstal (Russia). Mechanical activation of the slag and mixtures was performed in the Vortex Electromagnetic Activation setup, consisting of non-magnetic chamber, loaded with treated material and magnetic bodies (cylinders with 2 mm diameter and 15-20 mm length). Traveling magnetic field is circular to the chamber, forcing milling bodies to move and
activate loaded sample. Typical load of slag and/or additives was 100 g and 200 g of milling bodies were loaded. Typical activation time was 2-7 minutes.

Reference samples were produced by milling of slag particles in ball mill loaded with steel balls (12 mm dia.). PQ-N2 planetary ball mill was used for experiments with typical activation time 120-180 minutes.

Size distribution and morphology of mechanically activated samples were investigated using Scanning Electron Microscopy (Tescan Vega 3, Czech Republic) and Dynamic Light Scattering (Fritsch Analysette 22, Germany). For SEM investigation powder samples were glued on conductive carbon tape and placed in microscope chamber without additional treatment. DLS experiments were performed with dry powders dispersed in the DLS setup using integrated dispersion system.

3. Results and discussion

Scheme of the vortex layer activator (VLA) is shown in figure 1. VLA setup is designed for production of homogeneous mixtures of metallic, oxide and ceramic powders using travelling magnetic field and ferromagnetic agitators. Mechanical activation and mixing is provided due to high-speed rotation of ferromagnetic rods in rotating magnetic field, resulting in formation of pseudo-fluidized bed regime.

![Figure 1. General view of VLA setup.](image)

Laboratory setup used for experiments consisted of reactor with internal diameter 67 mm, and length of the work zone 180 mm. Typical size of the agitating rods was Ø2×20 mm. Technological parameters of the setup were calculated using common theory of the constrained motion.

The volume of the reaction chamber \( V_{\text{react}} \) is 634 cm\(^3\), volume of the agitating rod \( V_{\text{rod}} \) is 0.0628 cm\(^3\). Thus knowing typical critical parameter for the VLA setup \( K = 0.04…0.05 \) amount of rods can be easily calculated as: \( x = K \times (V_{\text{react}} / V_{\text{rod}}) = 400…600 \).

Various loading of rods as compared to slag was investigated. The main goal was to obtain the lowest size of activated slag particles and at the same time to keep uniform distribution of particles.
Details of the experiment are shown in Table 1 for 100 g of slag with different amount of steel agitating rods and various treatment times.

Table 1. Parameters of VLA mechanical activation of metallurgical slag.

| Treatment time | 3 minutes | 5 minutes | 7 minutes |
|----------------|-----------|-----------|-----------|
| Slag : rod ratio | 1 : 2 | 1 : 2 | 1 : 2 |
|                | 1 : 2.5 | 1 : 2.5 | 1 : 2.5 |
|                | 1 : 3  | 1 : 3  | 1 : 3  |
|                | 1 : 3.5 | 1 : 3.5 | 1 : 3.5 |
**Figure. 2.** SEM images (left) and particle size distribution (right) for VLA-activated samples with “slag:rod” = 1:3: a) – 3 minutes, b) – 5 minutes, c) – 7 minutes.

SEM images and particle size distribution of typical activated samples with “slag:rod” ratio 3 and various milling time are shown in figure 2. As it can be seen from the data shown in figure 2, mechanical activation during 3 minutes allows one to obtain uniform particle size distribution with maximum in range 7-10 μm. Increase of the time of the treatment results in polymodal dispersion of particles with increase of amount of particles with size higher than 50 μm. This may occur due to aggregation of particles and high-energy impacts during activation process.

Power parameters of VLA mechanical activation process and planetary ball milling were compared for samples with similar particle size distribution. Specific surface area was measured for typical samples using BET technique.

Using the VLA approach allows to reach SSA values in range 6-7 m²/g. Note that the same process realized by planetary ball mill results in SSA values much lower, namely 1-1.5 m²/g.

Energy consumption data for both cases is shown in Table 2. As it can be seen, it is necessary to use longer period of time with planetary ball mill in order to produce samples with similar parameters as compared with VLA-produced materials.

As one can see from the data presented in Table 2, VLA process is 3 times more energetically effective as compared with planetary ball mill, which may be due to higher specific energy transferred by agitating rods as compared with relatively low-speed movement of milling ball in planetary mill.

**Table 2.** Energy consumption data for VLA and planetary ball milling mechanical activation.

| Type of setup          | Nominal power, W | Treatment time, min | SSA value, m²/g | Energy consumption, KWh/kg |
|------------------------|------------------|---------------------|-----------------|---------------------------|
| VLA                    | 2100             | 3                   | 6.8±0.4         | 1.050                     |
| Planetary ball mill PQ-N2 | 750             | 120                 | 1.2±0.06        | 3.750                     |

4. Conclusion

Vortex-layer activation was successfully adopted for production of microscale mechanically activated metallurgical slag. Obtained materials show uniform particle size distribution and can be used as a source for clinker-free cements for construction applications.

Technological parameters of VLA-process were optimized, showing 3 minutes as an optimal time to produce good distribution and microscale particles.

VLA process was shown to be 3 times more energetically effective as compared with traditional planetary ball mill. Thus, this approach can be of future importance for industrial-scale applications.

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