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Granular aggregate for fill mortars using blast furnace slag

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Abstract. The technology of underground mining is one of the most promising areas of the mining industry. The use of technogenic waste, as well as unclaimed and substandard raw materials for the production of fill mortars in all over the world is an urgent problem in ecology and materials science. Research on obtaining the compositions of backfill mortars with different contents of blast furnace slag is presented. Mechanical activation of raw mixtures for granular aggregates was carried out in a vortex jet mill. A method for preparing raw material granules in a disc granulator has been developed. It has been established that when using a disc granulator, the following yield of aggregate fractions has been obtained: the number of fractions up to 8 mm is 30 %, fractions up to 6 mm – 27 %, fractions 2–4 mm – 43 %. It has been marked that granular aggregates using a slag fraction of 2.5 mm (composition 1) have the greatest strength of 3.73 MPa. When the fraction size increases up to 5 mm (composition 1), the strength of the granules decreases by 12.01 % and amounts to 3.33 MPa. The structure formation of solutions with different types of granular aggregates has its own characteristics, which are determined by the slag fraction, composition and water-binding ratio, as well as the condition of strength gain.

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1. Introduction

The object of the study is backfill mixtures that meet the operational characteristics for the effective backfill of mined-out spaces of mining enterprises.

The mining industry in the modern world is one of the main developing areas both in the Russian Federation and abroad. The extraction of iron ores and their processing leads to the formation of a fairly large number of by-products – slag, which must be disposed of, as they cause serious environmental problems, which is one of the important problems for the modern world [3].

Currently, many studies have been carried out on the possibility of using blast furnace slag in the production of building materials, including for use in the cement industry, this is due to the similarity of the chemical and mineralogical composition with Portland cement [1, 2, 4]. Blast furnace slag is crushed in efficient mills to achieve the required slag fraction, and then used as a mineral additive in the preparation of various types of cements and binder compositions [5, 6].

In backfill mining, filling compounds based on Portland cement are widely used as a binder and fine aggregate. At the same time, cement in filling mixtures is used in huge quantities, which leads to its overconsumption and affects the economic costs of iron ore mining and the maintenance of the mining complex [6–8]. Analysis of statistical data indicates that a significant share of the cost of the filling mixture belongs to Portland cement.

To prepare effective filling mixtures, it is necessary to have fine aggregates of a certain required granulometric composition, ensuring the rational use of the binder, guaranteeing the formation of high density and strength of filling mortars [12]. Unfortunately, in many regions of our country and abroad, where various mineral resources are mined, there are no effective fillers that ensure the formation of the necessary structure of backfill masses. When developing and using fill masses, you should take an individual approach to the geological features of the mined-out space, its condition, as well as the development and placement of fill mixtures, which requires additional technical, financial solutions and investments [9]. The main way to reduce the cost of production of backfill mortars is to obtain backfill mixtures with optimal technical and economic indicators, which requires the development of effective granular aggregates that ensure the rational use of Portland cement and the production of reliable and durable backfill mortars [10, 11, 13].

To date, there have been a number of scientific studies [14, 17, 18] related to the production of granular aggregates based on Portland cement and various technogenic raw materials.

It is noteworthy that in order to create cost-effective compositions of granular aggregates, it is necessary to select appropriate binder compositions [4, 7, 15].

The production of effective filling mixtures that meet the technological and physical-mechanical characteristics for filling mined-out voids for a mining enterprise is a very important task.

When developing various compositions of backfill masses to save material and technical resources, various mining enterprises use local and technogenic raw materials [16, 19, 20]. In many regions of our country and abroad, due to the peculiarities of the geological structure, there is a shortage of high-quality and fine aggregates. Therefore, in this regard, the development of granular aggregates with a certain composition that guarantees the production of high-quality and dense solutions and concretes for their intended purpose is relevant.

The goal of the research is to create effective backfill mixtures that meet the technological and physical-mechanical characteristics for backfilling mined-out voids for a mining enterprise.

The following tasks were solved within the framework of this study:

- Development of a composition with different dosages of slag in a percentage ratio from 85–95 %;
- Production of raw spherical granules by rolling in a plate granulator with a size of 2.5–10 mm;
- Analysis of the results of sieving the obtained granules using a plate granulator of fractions from 2–8 mm;
- Evaluation of the effectiveness of the application of physico-chemical characteristics of granular aggregates in fractions of 2.5, 5, 10 mm and strength indicators of granular aggregates with an increase in the size of fractions in the developed voids for mining enterprises.

2. Materials and Methods

The production of granular aggregates involved the selection of compositions, the study of their properties, preparation of raw granules according to the proposed method, and the study of the properties of the resulting granular aggregates.

At the first stage, compositions with different dosages of slag were obtained.

When developing compositions for various granular aggregates, three compositions 1, 2, 3 were studied; for comparison, commercial Portland cement TsEM 0 Interstate Standard GOST 31108-2020 manufactured by Belgorod Cement CJSC was used; blast furnace slag of a fraction ≤0.16 mm from Severstal PJSC was used as a mineral additive [21–23].

The preparation of compositions 1, 2, 3 was carried out in a VSM-01 vortex jet mill by grinding to a specific surface of about 600 m^2/kg.

Table 1. Composition and specific surface.

Code	Composition of the composition, %		Specific surface area before and after passing through VSM-01, m^2/kg	
	PC	**Slag**	**before grinding**	**after grinding**
PC	100	–	305	–
1	5	95	325	604
2	10	90	310	590
3	15	85	290	576

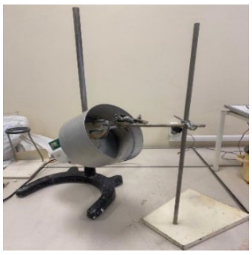
During mechanical activation of compositions in a vortex jet mill, the specific surface area of compositions with different slag contents: 85, 90, 95 % changed, respectively, to 1.98, 1.9, 1.85 times.

Granulated aggregates from the given compositions were obtained in a disc granulator.

3. Results and Discussion

The laboratory installation is a cylindrical metal plate (bowl) with sides, to which a motor is attached, secured by a holder. The granulator is equipped with an inclination change device, a scraper device consisting of a combination of a non-powered scraper and a cleaning scraper, and is used to make balls (pellets) at the same time as bottom cleaning and edge cleaning to form balls. A general view of the laboratory granulator is shown in Figs. 1a, 1b.

(a) laboratory granulator



(b) laboratory granulator

(c) granular preparing mix

(d) granular obtaining process

(e) granular obtaining process

(f) granular obtaining process

Figure 1. General view of a laboratory granulator and stage-by-stage granular obtaining process.

The production of raw material granules was carried out by the pelletizing method. Rolling involves a group of processes that are characterized by the movement of granulating powder over the surface of the device. The dry mix, located in a disc granulator, is irrigated with distilled water using a sprayer (Fig. 1c). At the same time, the surface of the powder in the disc granulator is moistened and, due to the rotation of the bowl, small granules begin to form, which, when in contact with the dry powder, increase in diameter. As the bowl rotates, the granules are further rolled to the required diameter (Figs. 1d, 1e, 1f).

In the granule pelletizing process, powder agglomeration is a crucial step essential for practical implementation. Continuous movement of the granular material facilitates both the formation and enlargement of granules, as well as their potential destruction due to fluctuations in humidity and variations in the adhesive properties of the material layers being rolled. The objective during agglomeration is to establish conditions conducive to the formation and preservation of granules with diverse diameters [24–27].

A typical pellet granulation setup involves a horizontally or slightly inclined rotating plate, onto which powder is fed, typically with a binding liquid. The wet particles undergo agglomeration and rolling to achieve the desired density and size. However, deviations from optimal granule growth may occur due to individual granule connections or breakage, resulting in diminished granule quality.

As the plate rotates, a portion of the powder adheres to its walls and base, ascending to a certain height before descending. The ascent height and powder capture rate depend on various factors such as internal and external friction ratios, rotation speed, and unit filling level. During ascent, the granules move in tandem with the base, maintaining relative immobility until reaching a point where compression occurs, initiating rolling and subsequent granule enlargement. The process of rolling granules in a laboratory granulator occurs within 10 minutes until the required maximum diameter of 10 mm is reached.

When developing the technological basis for producing granular aggregates using mineral powders and binders, the hardening conditions of the resulting rounded particles are important, since binders harden differently under different conditions. The prepared granules hardened and gained strength under normal conditions (ambient temperature +20 °C and relative humidity 80–90 %).

Ready-made granular aggregates are fairly tightly compressed solid spherical particles ranging in size from 2.5 to 10 mm (Fig. 2).

Figure 2. Grained filling aggregates.

Analysis of the results of sifting the resulting granules showed that when using a disc granulator, the highest content of the fraction up to 8 mm is obtained, which is 30 %, fractions up to 6 mm – 27 %, and the fraction from 2 to 4 mm is present in larger quantities in the amount of 43 % (Fig. 3).

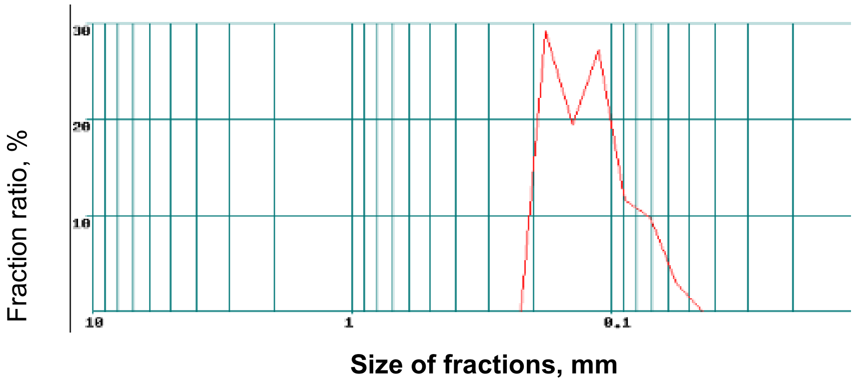


Figure 3. Granulometric size grading.

The Michaelis apparatus was used to determine the compressive strength of the resulting granules. The resulting granule of a certain fraction was placed between special clamping plates of the device, and the handle was twisted to tightly press the granule to the plates. Next, a bucket was placed on the hook and the shot began to be poured evenly until the moment when the bucket with shot set the lever in motion. Then the bucket of shot was weighed and the compressive strength of one granule was obtained in gc/mm^2.

Testing of the resulting granules was carried out 28 days after complete hardening and drying. Granular aggregates obtained in a laboratory setup are shown in (Fig. 4).

Figure 4. Granulated aggregate, obtained in a laboratory facility.

The results of physical and mechanical tests of the obtained granular aggregates are shown in (Fig. 5).

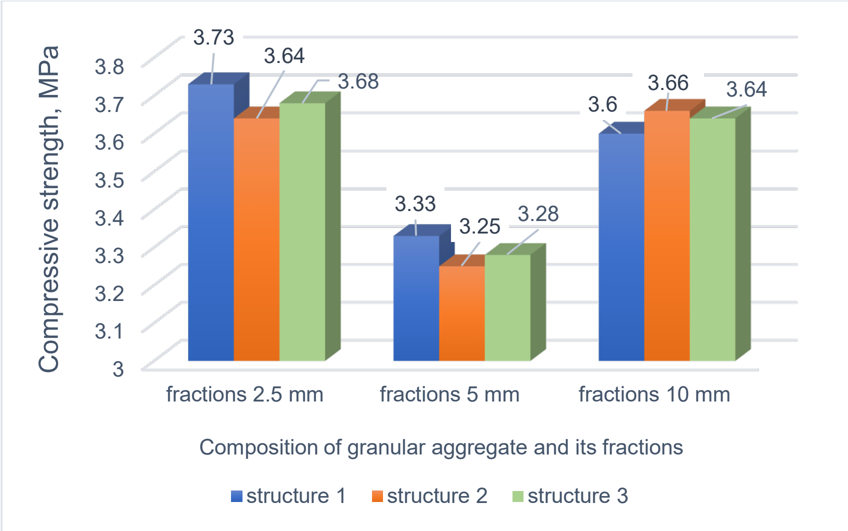


Figure 5. Physico-mechanical characteristics of granular aggregates by fractions.2.5, 5, 10.

Analysis of the results of physical and mechanical tests of granular aggregates showed that a certain technical effect was achieved. It has been established that granular aggregates using a slag fraction of 2.5 mm (composition 1) have the greatest strength of 3.73 MPa. When the fraction size increases to 5 mm (composition 1), the strength of the granules decreases by 12.01 % and amounts to 3.33 MPa relative to 2.5 mm granular aggregates. When the fraction size increases from 5 mm (composition 1) to 10 mm (composition 1), the strength increases by 8.11 % and amounts to 3.6 MPa.

In accordance with the stated goal of creating granular aggregates for backfill mortars, it was of interest to determine the strength characteristics of their various fractions in cement mortar. In this regard, cube samples were molded as follows: 1) prepare a cement mortar with W/C = 0.5; 2) granular aggregates of different fractions with the same mass were weighed; 3) the mixture was mixed and placed in sample cubes, while granular aggregates in all forms occupied the maximum volume with their same mass. This type of molding was justified by the creation of such a macrostructure of cement stone with filler, in which the nature of the destruction of the samples will be realized with a gap in the places of grains of granular filler, that is, in the most weakened areas. Molded cubes 3×3×3 cm gained strength within 28 days under normal conditions.

During the research, 18 sample cubes were molded from 3 types of recipes. Laboratory tests of cube samples were carried out on a hydraulic press PGM-50MG4. Figs. 6, 7, 8 show destroyed samples of the compositions.

Figure 6. Mortar sample chipping with granular aggregate 2.5 mm fractions.

Figure 7. Mortar sample chipping with granular aggregate 5 mm fractions.

Figure 8. Mortar sample chipping with granular aggregate 10 mm fractions.

As a result of the study of chipped surfaces of the tested samples, a type of destruction was revealed, characterized by the predominant rupture of filler granules. It has been established that all granules in fracture zones have maximum diametrical dimensions; therefore, destruction occurs precisely at the radial distance from the contact zone of granules and cement stone.

It is important to take into account the porosity of granular aggregates and their features in the composition of the solution. Having carried out a comparative analysis of Figs. 6, 7, 8, it should be noted that the contact zones of granular aggregates (slag) and cement stone of the destroyed sample have clearly visible interface lines, when, as the diameter of the slag granules in the aggregates increases, these lines are blurred.

This suggests that the connection between granular aggregates and cement paste, due to an increase in the porosity of the former, increases, and therefore the optimal aggregate, from the point of view of the integrated operation of the entire composition of the mortar mixture, is an aggregate with a diameter of 2.5–10 mm. The size of the contact layer increases with decreasing binder content in the composition of the granular aggregate.

Thus, the process of structure formation of solutions with various types of granular aggregates has its own characteristics, which are determined by the use of slag of one or another fraction, the type of binder component and its percentage, water-binder ratio, conditions for strength development and other parameters.

In the study of granular slag aggregate in cement composites, when compared with carbon nanostructure in primary aluminum production, key parallels and differences in the relationship between structure and properties, interfacial interaction and optimization strategies are traced between them.

Table 2. Similarities in Structural Behavior & Failure Mechanisms.

Aspect	Slag-Cement Composites	Carbon Nanostructures in Aluminum
Interfacial Bonding	Weakest link is granule fracture (not ITZ); porosity improves adhesion.	Carbon nanostructures influence anode/cathode interfaces; poor bonding leads to inefficiencies [24].
Optimal Particle Size	2.5–10 mm slag granules maximize strength.	Nanoscale carbon (e.g., nanotubes) enhances conductivity but requires dispersion control [5].
Porosity Effects	Higher slag porosity improves mechanical anchoring.	Porous carbon anodes affect electrolysis efficiency and durability [17].
Failure Analysis	Radial cracks in granules dominate failure.	Carbon anode degradation due to microcracking/spalling [8].

Table 3. Contrasts in Material Systems & Applications.

Parameter	Slag-Cement Composites	Carbon in Aluminum Production
Primary Material	Industrial slag (SiO_2, CaO, Al_2O_3).	Carbon (graphite, nanotubes) [14].
Key Interaction	Slag-cement chemical/physical bonding.	Carbon-electrolyte/oxide reactions [23].
Performance Goal	Mechanical strength, durability.	Electrical conductivity, thermal stability [13].
Destruction Mechanism	Granule fracture under tension/compression.	Anode erosion/corrosion via electrolysis [22].

Both studies highlight:

Interfacial Engineering:

- Slag porosity boosts cement bonding;
- Carbon nanostructures modify electrode interfaces.

Size-Dependent Properties:

- Slag granules (2.5–10 mm) optimize mortar strength;
- Nanocarbon size/shape affects aluminum electrolysis efficiency.

Process Optimization:

- Binder content, curing conditions;
- Carbon purity, electrolysis parameters.

3.1. Industrial Implications

Results using slag:

- Waste slag reuse in construction (circular economy);
- Guidelines for durable, low-cement composites.

4. Conclusion

In accordance with the set objective, the following results were obtained:

1. Granular fillers for cement slurries with different slag content were developed, which were obtained in a laboratory granulator.
2. A method for preparing raw material granules was developed. Studies have shown that the granulometric composition of the obtained granular fillers includes the highest content of fraction up to 8 mm, which is 30 % of the total volume of finished granules, fraction up to 6 mm is 27 %, and fraction from 2 to 4 mm is present in greater quantity in the amount of 43 %.

The obtained physical and mechanical results indicate that granules of fraction 2.5 mm (composition 1) have the highest strength of 3.73 MPa, which allows using them as granular fillers for cement slurries.

A study of the chipped surfaces of destroyed granules revealed their strong adhesion to the cement stone. The obtained granulated filler is of considerable interest for use in the development of mortars and fine-grained concrete in regions where high-quality fine fillers are not available.

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