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ASSESSMENT OF AN EXPEDIENCY OF BINDER MATERIAL MECHANICAL ACTIVATION IN CEMENTED ROCKFILL

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ABSTRACT

This study is aimed to assess the expediency of applying the binder material mechanical activation in a cemented rockfill (CRF), consisting of ground smelter slag, waste of limestone and rock refuse at one of the largest mines, as well as at any other mines which use these components for CRF. The polynomial dependences have been obtained of strength variation of the CRF, which is used in the conditions of studied mine, on the time of consolidation and the ratio of backfill materials. In the CRF mixtures, the mechanical activation was carried out of the granulated blast-furnace slag, and the compliance has been assessed of CRF with the design strength of the backfill massif. In the studied conditions of the ore mine, with ratio of a binder material to filler of 0.5 and the existing cost of backfill materials, the use of mechanical activation of the binder material according to the two-stage grinding scheme turned out to be insufficiently expedient, since the production cost (materials + grinding) of the most economical backfill mixture is only 2.8% less compared with a basic composition. It is noted that the expediency of using the mechanical activation depends on the remoteness of the mineral raw material base, especially the main inert filler that significantly increases the cost of backfilling works. It is shown that in the operating conditions of other mines with a similar component proportion and a close rich mineral raw base, the mechanical activation of the binder material can be enough effective. It has been determined that with an increase in ratio of C_{bin}/C_{in} from 1.0 to 4.6, the difference in costs for the backfill mixture production in the considered compositions, where mechanical activation was performed, increases in a positive direction, but for the most economical backfill mixture, if compared to the basic one, it will be changed from 16.8 to 46.0%. An attention is focused on possible ways to increase the expediency of applying the mechanical activation of the binder material by means of forming the backfill massif with different strength along the height of the stope chamber.

Keywords: cemented rockfill, mechanical activation, binder material, inert filler, CRF strength, energy-efficient fine grinding.

1. INTRODUCTION

As a result of functioning of the mining and metallurgical sector enterprises, an accumulation of large-tonnage industrial wastes on the earth surface in the form of dumps and tailing dumps is inevitable and this leads to an environmental pollution [1-4]. To solve these ecological problems, these wastes are widely used as components of backfill mixtures for filling the mined-out space, and due to which they are disposed of in underground cavities and areas of the earth surface are being cleared [5-8]. This provides for the minimization of the earth surface deformation, increases the safety of mining operations, reduces the ecological burden on industrial regions, and also significantly increases the completeness of the reserves extraction with minimal losses and dilution. The issues of complete extraction of various minerals types from the subsoil are constantly relevant [9-10].

At present, non-ferrous and ferrous metal ores in Australia, the USA, Canada, Finland, Sweden, China, in the countries of the former Soviet Union, etc., are mined by systems of development with consolidating backfilling. The introduction of backfilling technology in a number of ore mines indicates the effectiveness in the use of these development systems, despite the additional costs that are covered by the obtained products quality and, in most cases, the lack of dressing costs.

The accumulated experience in the world of underground mining of ores of precious, ferrous and non-ferrous metals with backfilling shows that the cemented paste backfill - CPB has become widely used, which consists of Portland cement and various types of mine refuse [11-13], and to a lesser extent the cemented rockfill - CRF is used, consisting mainly of cement, smelter slag, fly ash, crushed rocks, granites and other rocks [14, 15]. In the countries of the former Soviet Union, the CRF based on ground smelter slag, crushed rocks, crushed stone, limestone, mine refuse, sand, etc. is primarily used in mines [16, 17]. The widespread use of CPB in world practice is conditioned by the expediency of constructing a simple and cheap backfilling complex with an insignificant consumption of cement (3-5%) in the mixture, and the availability of mine refuse in almost all mines. The use of smelter slags as a binder material, including the transportation from metallurgical plants to the mine and their preparation (grinding), is more expensive than the cost of cement, therefore CPB is more efficient. However, with large mines production capacities and, accordingly, the volumes of backfilling works, the increased requirements for backfill strength (7-10 MPa), which is typical for mines in countries of the post-Soviet period, the use of cement as the main binder, and, therefore, CPB is not economically expedient, thus CRF is preferable.

For effective CRF use, there should be an availability with sufficient reserves of the mineral raw base of binding and inert materials, both of natural and technogeneous origin. The availability of a rich mineral raw base of resources to provide the CRF with components and their remoteness from the mine

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predetermine a wide variety of possible mixture formulations and their economic efficiency.

The development of mining operations in depth of ore field is accompanied by the complication of mining and geological conditions caused by rock pressure increasing with depth, as well as the impact of blasting operations on the massif, which entails a decrease in the backfill massif stability due to the destruction of its vertical and horizontal outcropping [18-20]. These negative phenomena make it necessary to revise the compositions of backfill mixtures and search for cost-effective ways to improve their structural and strength properties or to conduct research into management of the viscoplastic state of the backfill massif [21-23].

Increasing the strength characteristics of CPB and CRF is possible due to the mechanical [24-26], chemical activation of components [27-30] or adding the foreign specific materials [31, 32]. Furthermore, with an increase in the dispersion of binder materials, an improvement in the backfill massif structure and an increase in the strength characteristics are noted [33]. As a rule, for the preparation of a binder material, usually of granulated blast-furnace slags and with CRF, a Ball Mill is used according to one-stage grinding scheme. In such conditions, the mechanical activation of the binder material is not effective to perform, because the energy consumption for grinding increases significantly [34]. The possibility of using the two-stage grinding schemes, when preparing a binder material, is relevant, above all, for consideration in terms of the CRF application, where the binder material is preliminary grinded by wet grinding. Currently, the scientific literature does not pay enough attention to the aspects of determining the area of expedient use of mechanical activation when performing the backfilling works.

This study is aimed to show how expedient it is to apply mechanical activation in CRF by the example of a component composition which consists of ground smelter slag; limestone and rock refuse from one of the large mines with account of the different ratio of costs of the binder material and inert filler.

2. PECULIARITIES OF BACKFILLING WORKS EXECUTION WHEN DEVELOPING THE PIVDENNO-BILOZERSKE FIELD

One of the mining enterprises that develop the high-grade iron ores with an iron content of more than 60% by underground mining method in the Pivdenno-Bilozerske and Pereverzivske fields is the PJSC "Zaporizhzhia Iron Ore Plant". The share of the enterprise in underground mining of Ukraine is 25-30%, and the development of reserves is carried out by a highly efficient sublevel-chamber system of development with CRF [35]. As a component of the backfill mixture, waste of mining and metallurgical production is disposed of in the underground space: ground smelter slag (binder material), waste of limestone and rock refuse from mining operations (inert filler), which, when being mixed with water, turn into a solid monolithic massif. The significant volumes of blast-furnace slag have been accumulated in Ukraine as a result of iron and steel smelting, which is a sufficient mineral raw base for the binder material [36].

Figure-1 demonstrates in detail the geographical location of the mining enterprise, within the mining allotment of which the backfilling complex is located, with a working capacity of up to 300 m^3/h.

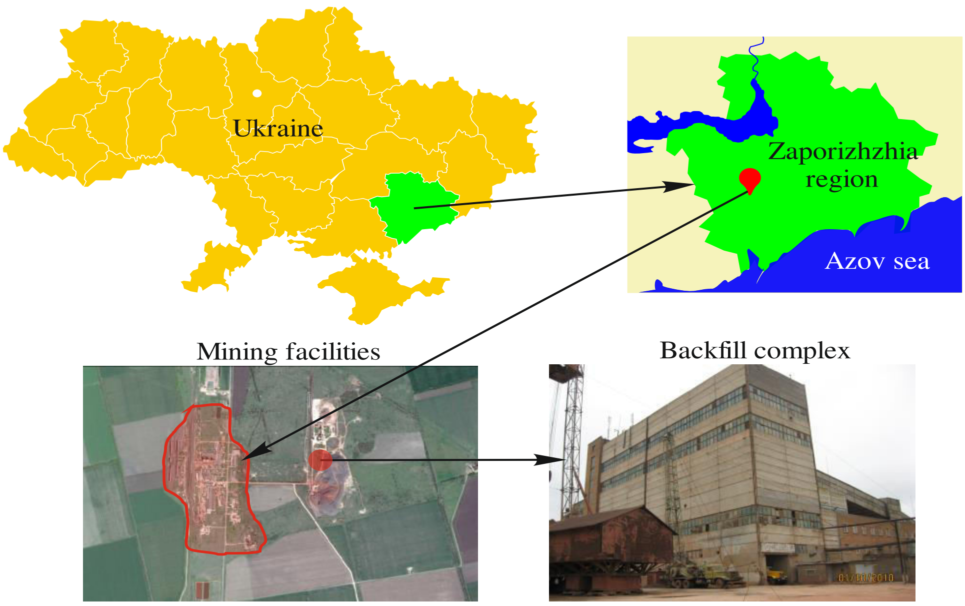

Figure-1. Location of the PJSC "Zaporizhzhia Iron Ore Plant", which develops the iron ore reserves of the Bilozerskyi iron-ore region with the CRF application.

As can be seen from Figure-1, a rock dump is located near the complex, which serves as the source of a part of inert filler in the composition of the backfill mixture (25-50%), for the delivery of which there is no need in high costs for transportation. The use of crushed rock refuse in the proportion of a mixture has significantly reduced the cost of backfilling works.

PJSC "Zaporizhzhia Iron Ore Plant" annually produces huge volumes of backfill mixture, which exceed 1 million m^3. The formulation of the used mixture consists of the components represented in Table-1.

Table-1. Component proportion of the backfill mixture.

Component name	Proportion in the backfill mixture, %	CRF strength, MPa		
		30 days	90 days	180 days
Granulated blast-furnace slag	22.3	3.0-4.0	6.0-7.0	8.0-9.0
Flux limestone waste	38.0			
Crushed rock refuse	24.1			
Water	15.6			

The backfilling complex consists of a receiving point for bulk backfill materials, warehouses for these materials, and the main building where the components mixer unit is located. The granulated slag and waste of flux limestone are routed to the chain of main building apparatus by separate conveyor lines. The mine rock is exposed to crushing in a jaw crusher, located on the rock dump, to 20 mm fraction, and enters the main building of the backfilling complex by the railway. The grinding of the granulated blast-furnace slag is carried out according to the one-stage grinding scheme by wet grinding with two Ball Mills of the MShTs 36×55 type with a working capacity of 60 t/h each one (Figure-2).

Figure-2. The Ball Mill of the MShTs 36×55 type for wet grinding of the granulated blast-furnace slag.

The density of the pulp, containing ground slag particles, on exit from the mill ranges from 1.45 to 1.55 g/cm^3, while the fractional yield is 50-60% of particles with coarseness of - 0.074 mm, which corresponds to a specific surface area of up to 2000 cm^2/g. The flux limestone, crushed rocks and slag sludge are mixed in a C-892 type mixer unit, and, by a backfilling pipe are fed into the underground space. The mined-out stope chambers are filled with the backfill mixture in layers due to the necessity of its solidification in the first portion (chamber bottom), and the presence of 4 sublevel mine workings in order to avoid outbreak of the dams.

The technological schemes for preparing the backfill mixtures, as well as equipment for grinding the source material, have not been modified since the implementation and wide distribution of this backfilling type in the ore fields of the post-Soviet countries, despite the constant decrease in the depth of mining operations, as well as rising prices for the acquisition of backfill materials and electrical power. The decrease in the production costs and improving the quality of backfill massif is a relevant issue in case of large scope of backfilling works.

It was evidenced by our previous studies that the fineness of grinding the binder material particles of 50-55% in a Ball Mill with coarseness of - 0.074 mm does not fully provide for the binding properties of the blast-furnace slag. With a further increase in its degree of dispersion to 92%, a significant increase in strength by 2.0-2.5 times is noted, but at the same time, the energy consumption for grinding increases. The lack of studies on energy-efficient fine grinding technologies when performing the backfilling works has led to the restriction of the mechanical activation development of binder materials.

It is supposed to study and predict the cost of 1 m^3 backfill mixture production by two-stage slag grinding with the use of a Ball Mill and an energy-efficient mill at the re-grinding stage and, then, to assess the expediency of using this variant for preparing a binder material in case of different prices for backfill materials.

3. METHODS OF RESEARCH

The mechanical activation of the binder material is possible by increasing the specific surface area of its particles at the stage of the backfill mixture preparation. In order to assess the effectiveness of the mechanical activation of granulated slag, 5 experimental backfill mixtures were prepared in the laboratory of the backfilling complex: No.1 mixture is similar to that used in the technology of backfilling works of PJSC "Zaporizhzhia Iron Ore Plant", that is necessary for comparison; in No.2-5 mixtures, the supply of granulated slag and the specific surface area of its particles was varied through mechanical activation. The backfill mixture includes the following components: binder material - ground blast-furnace slag, inert filler - waste of flux limestone and crushed rock refuse, as well as water for mixing. The data on the experimental backfill mixtures are presented in Table-2. As a result of reducing the consumption of granulated slag, the missing volume was compensated by a proportional increase in the share of inert filler - by means of waste of flux limestone and rock refuse.

Table-2. Characteristics of experimental backfill mixtures.

Number of the mixture composition	Proportion of "binder material-filler"	Actual specific surface area of slag particles, cm^2/g
No.1 backfill mixture (PJSC "Zaporizhzhia Iron Ore Plant")	**1:2.8**	**2000**
No.2 backfill mixture	1:5.2	2800
No.3 backfill mixture	1:5.2	4300
No.4 backfill mixture	1:11.5	2800
No.5 backfill mixture	1:11.5	4300

In order to prepare No.1 mixture, the granulated blast-furnace slag was ground to a specific surface area of 2000 cm^2/g in a laboratory Ball Mill with 1 kg of loading. Then, for the preparation of No.2-5 mixtures, it was planned to increase the specific surface area of the slag particles down to the limits of 3000 and 4000 cm^2/g. For this purpose, a laboratory gas-jet unit USI-20 was used, which is located at the test site of the Institute of Geotechnical Mechanics (Dnipro, Ukraine) that was conditioned by a sufficiently long time of grinding in a Ball Mill and the difficulty of preparing the required amount of ground material for producing the batches of backfill mixtures. According to the empirical dependence [37], the necessary rotation velocity of the jet mill classifier was determined in order to obtain the required design value of the specific surface area: at 800 rpm, a specific surface area of particles of 3000 cm^2/g is achieved, and at 1200 rpm - 4000 cm^2/g. After grinding of the granulated slag, the specific surface area of its particles was determined with the help of the Tovarov device, and the obtained its actual values (Table-2) differ slightly (7%) from the design values. With the use of a Multisizer-3 grain analyser, the average particle diameter was determined at different specific surface areas: 40 μm - at 2000 cm^2/g, 26 μm - at 2800 cm^2/g, and 15 μm - at 4300 cm^2/g.

The preparation of the mixtures consisted of the following stages: firstly, the crushed rock was added to the tank, then the flux waste with blast-furnace slag were added and mixed in a dry state, after that water was added to the dry mixture and it was mixed again for 10 minutes. After that, the most important parameters of the backfill mixture were determined: the flow - with the help of a cone, time of setting - with the use of the Vicat apparatus, and the shearing stress value - by the Sternbek device. After determining the technological parameters, each composition of the backfill mixture was poured into metal moulds with size of 10×10×10 cm. The cassettes with the moulds were lubricated with technical oil in order to prevent the backfill mixture adhesion to the metal mould surface. In a day, the surfaces of the CRF samples of each composition were numbered. The backfill mixture was settled in the moulds for 3-4 days until complete loss of setting and complete drainage of water from the sample. Then, the moulds were removed, and CRF samples were placed in special storage racks. In this study, 45 samples in total were prepared and poured into moulds: by 9 CRF samples for strength test at the age of solidification of 30, 90 and 180 days. The uniaxial compression strength of the CRF was determined by crushing the samples in a hydraulic press. The CRF sample has been loaded in the press with a rate of 0.3-0.5 MPa. A press of the PSU-100 series with a strength scale of up to 10 MPa was used, and in the case of achieving the CRF strength of 10 MPa, a press of PSU-120 series was used with a loading value of up to 50 MPa. Some stages of the mixtures preparation are shown in Figure-3.

Figure-3. Laboratory studies of preparing the backfill mixtures and testing the samples for strength.

To assess the expediency of applying the mechanical activation, two variants of a backfill mixture preparation were compared with one-stage, traditional grinding (MShTs 36×55 type mill) of No.1 backfill mixture (Table-2) and two-stage slag grinding (MShTs 36×55 type mill and IsaMill) of No.2, 3, 4, 5 backfill mixture variants, by which the production cost of 1 m^3 of backfill mixture was determined with account of the price for materials and energy spent for grinding. The ratio of the binder material cost to the cost of inert filler from 0.5 to 4.6 was varied. The predicted energy costs at the first stage were determined according to the technical characteristics data of the Ball Mill, and at the second stage, based on the preliminary data of energy consumption by the IsaMill for grinding to the required dispersion [38].

4. RESEARCH RESULTS AND DISCUSSIONS

4.1 The influence of binder material mechanical activation on the CRF strength

The possibility of the backfill mixture application is considered in terms of its full satisfaction with transportable requirements, which if non-complied, can lead to blocking the mixture in the pipeline and arising an emergency situation. The measurements of cone slump of No.1-5 experimental mixtures showed that their flow varies from 10.3 to 11.2 cm and is within the regulatory limits of 10-12 cm. The shearing stress values for all mixtures varies from 0.55 to 1.01 MPa, the regulatory limit is 1.96 MPa. The time of mixtures flow loss varies from 15 to 18 hours, the regulatory limit is not less than 4 hours.

All batches of backfill mixture samples, which solidify at different set time, were exposed to uniaxial compression strength tests. In Figure-4, there are presented the results of studies on the dynamics of the CRF strength development over time at different consumption of granulated slag and its dispersion values. The definite advantage of the finely dispersed binder materials presence in backfill mixtures is an increase in strength.

The results (Figure-4) show that the strength of the CRF with different component proportion varies polynomially depending on the time of solidification, thus, demonstrating the positive dynamics in the strength increase. Thus, by reducing the consumption of granulated blast furnace slag and increasing its specific surface area, it is possible to achieve more significant CRF strength characteristics (No.2, 3, 4, 5 mixtures) than with the traditional composition (No.1 mixture). In addition, at the same consumption, but with the different specific surface area of granulated blast-furnace slag particles (No.2, 3 mixtures), the CRF strength is by 20-25% higher, and with the same specific surface area of the particles, but at different slag consumption (No.2, 4 mixtures), the CRF strength is only by 10-15% higher.

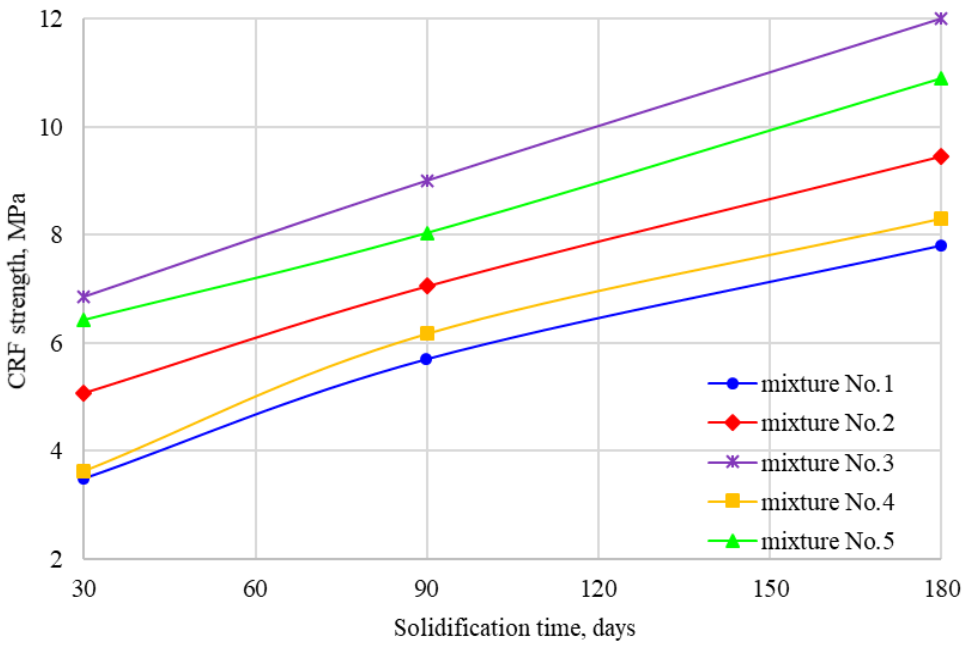

Figure-4. Dependence of the CRF strength on the time of solidification with different component proportion and specific surface area of the binder material particles.

It is possible to make a conclusion that the consumption of granulated blast furnace slag in the mixture has a less significant influence on the CRF strength if compared to the value of specific surface area of its particles, the importance of which in the formation of the backfill massif strength is incomparably greater. In addition to increase in the strength, an increase in the specific surface area of the binder materials has a positive influence on the development of stable bonds in the microstructure of backfill material, forming their needlelike fibrous type [33].

The backfill massif strength is also related to its stability, on which the quality depends of ore mined from the second-stage chambers, surrounded by the backfill massif. An increase in the CRF strength has a positive effect on the quality of the extracted ore reserves, since the probability of the backfill massif collapse decreases. At the moment of mining the second-stage chamber, the

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strength of the backfill massif of the first-stage chamber, laid down in the development depths of 640-840 m, should be 7.0-8.0 MPa, and with a further decrease in the depth, this index will increase. Usually, according to the order of chambers mining, the second-stage chamber in the mine field is developed not earlier than in half a year. Therefore, all the prepared backfill mixtures according to the strength characteristics at the moment of the second-stage chambers development will satisfy the specified standards.

4.2 Substantiation of effectiveness in applying the mechanical activation of the CRF binder material

Currently, a one-stage scheme with wet grinding of binder materials (mainly granulated blast furnace slags) is used in domestic mines for preparing the CRF, which makes it possible to achieve the grinding coarseness - 0.074 mm of particles up to 55-60%. In order to increase the fineness of grinding, the possibility of re-grinding the binder material is considered by using a two-stage grinding scheme.

Improving the process of mineral raw materials dressing in the mining industry undergoes a new stage of development and is marked by achievements in the creation of energy-efficient technologies. In particular, the world's leading companies in the mining industry use mills for fine and finest grinding of Metso production (VERTIMILL, SMD series) and Xstrata production (IsaMill series) for the process of re-grinding. The mills of the IsaMill series, which work with mixing the grinding medium, are characterized by the highest energy efficiency, ease of service and maximum energy efficiency [39, 40].

Further on, the use of this experience of dressing, when performing the backfilling works, is studied by the authors of the article. At the same time, it was made an attempt of an approximate and preliminary economic substantiation of the area of fine grinding application. The positive influence of fine grinding of ores during the dressing process on the reduction of electrical power costs is noted by many existing practice data. Thus, with a material coarseness of - 0.074 mm for over 90%, which is ground by IsaMill, the specific energy consumption is 9.1 kWh/t, while the Ball Mills consume 15-20 kWh/t, and in the re-grinding cycle the energy consumption is even more increased. According to preliminary assessments, IsaMill consumes by 2-2.5 times less electrical power for re-grinding of 1 ton of ore [41].

The studies conducted by AMMTEC Company for the scheme of processing the magnetite ore in Western Australia fields have shown that it is appropriate to use a Ball Mill for grinding to 100 μm with a content of 80% and subsequent magnetic dressing, and with final grinding to 34 μm in the IsaMill. Therewith, about 60 MW of electrical power is saved (40% of the total power and ≈50% of the power at the grinding stage) if compared to one-stage cycle in the Ball Mill [34]. The area of the IsaMill application is presented in details in the Company's materials [42].

For preparing the CRF on the basis of finely dispersed binding particles, in the technological chain of the backfilling complex, an IsaMill can be used, which develops a sufficient productivity of the final product coarseness and is able to grind materials with high hardness according to the Mohs's scale, in the present case the granulated blast furnace slags. In order to give an adequate economic assessment of the mill operation at the second stage, it is necessary to be guided by the energy indicators of grinding, i.e., to consider the particle coarseness of the final product. Caused by the lack of practical data on the slags grinding at the second stage in the IsaMill, the preliminary data of energy consumption was considered according to [38], where the product supplied into the mill contained 60% of particles of - 0.08 mm class, which, in general, corresponds to the fineness of grinding in a Ball Mill under the conditions of a backfilling complex at PJSC "Zaporizhzhia Iron Ore Plant". Based on the charts [38], the estimated specific energy consumption with account of the granulometric characteristics of ground slag, when increasing the dispersion by 1.4 times (from $S_{sp} = 2000$ cm^2/g to $S_{sp} = 2800$ cm^2/g), will be 10 kWh/t, and with an increase in dispersion by 2.1 times (from $S_{sp} = 2000$ cm^2/g to $S_{sp} = 4300$ cm^2/g) - 17 kWh/t. Under the conditions of PJSC "Zaporizhzhia Iron Ore Plant", when grinding the granulated blast-furnace slag by a one-stage scheme, 13 kWh/t is consumed. The cost of 1 kWh of electrical power at the enterprise is $0.074.

To assess the economic indicators of applying the mechanical activation, two variants are being compared of a backfill mixture prepared by one-stage, traditional grinding (MShTs 36×55 type mill) of No.1 backfill mixture (Table-2) and by two-stage slag grinding (MShTs 36×55 type mill and IsaMill) of No.2, 3, 4, 5 backfill mixture variants.

An important aspect is that if the consumption of the binder material in the mixture is reduced, then the reduced amount of the binder material is substituted by an inert filler or plasticizing agents. The economic efficiency of the fine grinding technology depends on this in a great extent, since in the case of expensive inert filler, which replaces the reduced part of the binder material, economic efficiency decreases. Thus, it is necessary in this case to simulate the situation as for the significance of costs of different components in order to establish the area of applying the mechanical activation. As a rule, waste of mining and metallurgical production is used as backfill materials, the price of which is set insignificant, but transportation of the material is a significant costly share. That mines which have a closely located mineral raw base of backfill materials have a lower cost of backfilling works. The cost distribution is presented in Figure-5 for the production of 1 m^3 of backfill mixture in the conditions of PJSC "Zaporizhzhia Iron Ore Plant" according to pricing data of 2014 (hryvnia against the dollar - 12.9).

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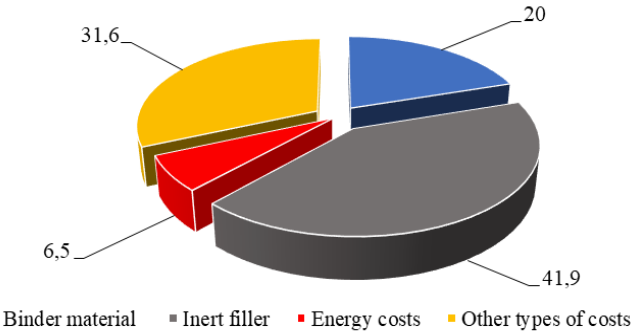

Figure-5. The cost distribution for the production of 1 m^3 of backfill mixture.

It follows from Figure-5 that inert fillers - waste of flux limestone with rock refuse - have the highest cost, which accounts for almost 42% of the materials cost in the backfill mixture. This is explained by its significant costs for transportation, since the distance to the pit is more than 200 km, and the granulated blast furnace slag of the metallurgical plant is at the distance of about 90 km. The use of flux limestone in the mixture is justified and is explained by the fact that the flux is an accompanying component and has a positive effect on the metallurgical conversion in the process of smelting the iron and steel. Therefore, in this situation, the use of mechanical activation is unlikely to be justified. However, other enterprises which have an adjacent mineral raw base with similar components may work with these components in the practice of backfilling works, and, therefore, in this case, the consideration of the mechanical activation issue will be relevant.

To assess the expediency of applying the mechanical activation by a two-stage grinding scheme in comparison with a one-stage scheme, it is necessary to predict the most important costs for the backfill mixture production. When modelling the costs, the following parameters were taken into account: the cost of the binder and inert materials, their consumption in the mixture, the ratio of components, the electrical power cost. The cost of grinding is an integral part, since the energy consumption of this process in the operation scheme of the backfilling complex is more than 70%. The cost of water for mixing is 0.004% of the CRF cost, therefore, when calculating, this category is not considered. The calculation results for filling the chamber of 100 thousand m^3 are given in Table-3.

The calculation results (Table-3) show that with the existing prices for CRF components and electrical power, the energy consumption used for grinding by a one- and two-stage grinding scheme, when satisfying the requirements of the design CRF strength under the conditions of the studied mine, the implementation of mechanical activation of the granulated blast furnace slag is not expedient. The main factor which reduces the expediency of applying the mechanical activation technology, when performing the backfilling works, is the high cost of the basic inert filler - flux limestone. This is caused by the initial highest cost of limestone and an increase in its quantity in the mixture together with the rock due to compensation of the volume with reducing the blast furnace slag consumption.

Inasmuch as a significant share of the cost for acquiring the materials is spent on backfill materials (almost 62%), according to Figure-5, it is advisable to simulate the situation at different pricing policies for binder material and inert filler, that will be useful for the backfilling work practice in other mines, which work under the similar technology and apply the similar backfill materials when filling the cavities. Based on the known data of component proportions of mixtures (No.1-5, Table-2), preliminary data on energy consumption (kWh/t) when grinding by one- and two-stage scheme, cost indicators on backfill materials, let us simulate the change in the costs of backfilling works and determine the ratio of prices of the binder material and the inert filler, at which it is expedient to use mechanical activation. The ratio is varied of the binder material cost to the inert filler cost C_{bin}/C_{in} from 0.5 to 4.6 and then we simulate the resulting costs (Figure-6).

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Table-3. Predicted comparison of costs of the backfill mixture production by one-stage and two-stage grinding of binder materials.

Number of the mixture	Volume of mixture, thousands m^3	Consumption of materials, t/m^3			Component price, $/ton			Costs of materials, thousands $	Energy consumption for grinding, kWh/t		Cost of electrical power, $/kWh	Cost of grinding, thousands $		Specific costs of 1 m^3 of mixture, $/m^3
		Slag	Flux	Rock	Slag	Flux	Rock		1-st stage	2-nd stage		1-st stage	2-nd stage	
No.1	100	0.5	0.85	0.54	3.63	4.05	1.34	743.2	13	-	0.074	50.5	-	7.93
No.2		0.3	0.95	0.64				741.6	13	10		29.02	22.3	7.89
No.3		0.3	0.95	0.64				741.6	13	17		29.02	37.9	8.08
No.4		0.15	1.04	0.7				747.9	13	10		14.5	11.1	7.72
No.5		0.15	1.04	0.7				747.9	13	17		14.5	18.9	7.79

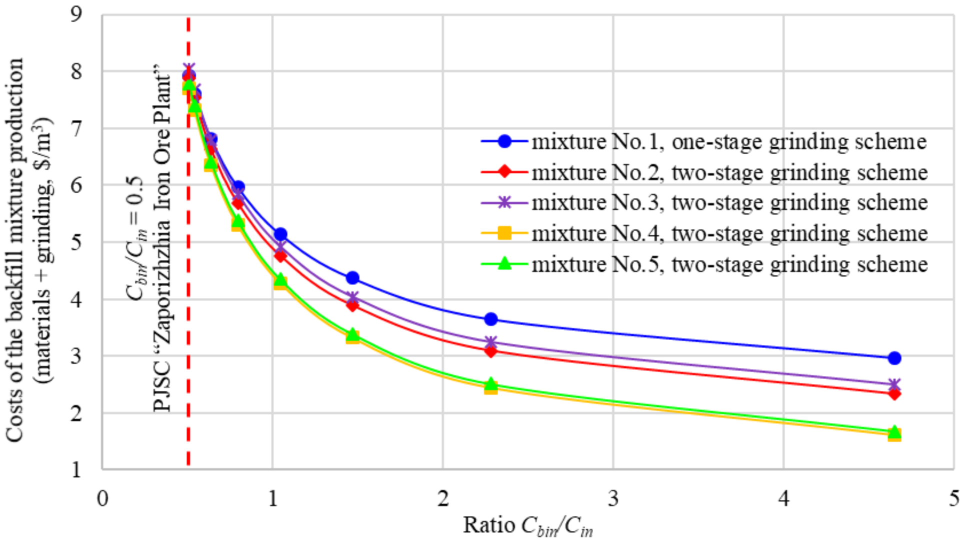

Figure-6. Change in the costs of the backfilling works execution depending on the ratio of prices of the binder material and the inert filler.

As it can be seen from Figure-6, the costs of the backfill mixture production are reduced significantly with an increase in the ratio C_{bin}/C_{in}. Thus, the most economical proportion of the backfill mixture from the above considered, is No.4 in relation to the basic mixture No.1. This is explained by the lowest consumption of blast furnace slag and, respectively, lower costs of its acquisition and grinding. In addition, as for No.4 mixture with a reduce in slag consumption, it is sufficient at the first stage of grinding to have in service one Ball Mill, which will also provide additional savings. It should be noted, that under the conditions of PJSC "Zaporizhzhia Iron Ore Plant" at a ratio of $C_{bin}/C_{in} = 0.5$ and existing price for backfill materials, it is inexpedient to use the mechanical activation of the binder material by the two-stage grinding scheme, since the cost of No.4 backfill mixture production is less by only 0.22 $/m^3 or 2.8% if compared to the basic mixture No.1. This difference should be considered as a low increment and it is unlikely to contribute to the rapid payback of the mill by the second stage of grinding and, respectively, such technical solutions will be characterized by low investment reliability [43]. This is conditioned by a lack of mineral raw base of backfill materials in this region. However, with an increase in C_{bin}/C_{in} from 0.5 to 1.0, the costs of all mixture variants (No.1-5) are sharply reduced by 35-45%, and the difference between the costs of mixtures No.1 and No.4 is already 0.86 $/m^3 or 16.8%. With an increase in the ratio C_{bin}/C_{in} from 1.0 to 4.6, the difference in costs of the backfill mixtures production with all considered proportions No.2-5 will increase even more positively, while for mixtures No.1 and No.4 there will be a change from 0.86 to $1.36/m^3 or from 16.8 to 46.0%. The other compositions (No.2, 3, 5) can also be considered, at which the costs are also less than at No.1, but still more than at No.4. For example, with further deepening of mining operations, the necessity will occur of increasing the CRF strength of more than by 8 MPa. Thus, in such conditions the basic proportions No.1 and No.4 by the strength factor may be insufficient and there will be a necessity to consider the backfill mixture proportions which have higher strength characteristics. In view of energy consumption data for grinding (kWh/t) and the power of mill drives with different standard sizes, the IsaMill 5000 will be suitable for the second grinding stage.

This prediction is advisable for mines that use CRF based on ground slag, limestone waste and their own rock refuse. The prediction algorithm itself can be applied to other proportions of backfill mixtures, since the distribution of binder components and inert fillers in 1 m^3 of backfill mixture in the mines is close to each other. If for the studied mine PJSC "Zaporizhzhia Iron Ore Plant" at specified prices, the application of mechanical activation is unprofitable, but in the conditions of other ore deposits development with the use of CRF, there may be, for example, a pit for the extraction of limestone located close to the mine, but a metallurgical plant with waste slag is distant (high ratio of C_{bin}/C_{in}). Therefore, in such a case, according to prediction (Figure-6), the use of mechanical activation in the backfilling works execution will be expedient.

In the case of expensive inert filler, it is necessary to sample and add to the backfill mixture the alternative materials in quantity of 20-30% by the inert filler weight, which will reduce its full cost. Such materials may include overburden clayey loams of pits, mine refuse, stone screening dust, etc. In case of a positive search for alternative replacement of expensive binder materials and inert fillers for cheaper ones, it is necessary to perform new studies on the slag mechanical activation in order to establish the influence of these materials on the CRF strength.

To improve the expediency of applying the mechanical activation of the binder material, it is also recommended to consider the formation of a stope chamber with different strength along the height of the backfill massif based on the study of its stress state using numerical or physical modelling [44, 45]. The obtained stress curves will make it possible to identify unstable areas of the backfill massif [46, 47], which should be primarily strengthened, and in the rest areas of the backfill massif, where critical stresses are absent, a lower strength should be formed with a more economical CRF proportion, that is, a differential approach should be performed to the backfill massif construction. The required CRF strength has a direct dependence on the consumption of the binder material and the value of the specific surface area of its particles that reduces the requirement to its strength. The costs of backfilling works are reduced and the expediency of applying the mechanical activation increases. This direction should be the subject of further research and is able to expand predicting the expediency of the mechanical activation in the backfilling works execution.

In conclusion, it should be noted that the expediency of applying the mechanical activation technology of the binder material in the backfilling works execution is fundamentally dependent on the mixture formulation, which provides the required strength to the backfill massif and has a certain ratio of binder material to the inert filler, as well as on the cost of the backfill materials conditioned by the remoteness of their locations. The costs of the backfill mixture production, when applying the mechanical activation, will significantly decrease with an increase in the ratio of C_{bin}/C_{in}.

5. CONCLUSIONS

The studies to assess the expediency of applying the mechanical activation of the binder material in the backfilling works execution made it possible to set the following results:

a) The polynomial dependences have been obtained of CRF strength variation on the time of consolidation, which is used in the conditions of studied mine, and a number of mixture proportions, in which the mechanical activation has been performed of the granulated blast-furnace slag. All experimental mixtures are able to form a backfill massif with design strength.

b) In the conditions of the studied ore mine PJSC "Zaporizhzhia Iron Ore Plant", at a ratio of $C_{bin}/C_{in} = 0.51$ and existing price for backfill materials, it is inexpedient to use the mechanical activation of the binder material by two-stage grinding scheme, since the production cost (materials + grinding) of the most economical backfill mixture is only 2.8% less compared with a basic proportion. This is caused by the remoteness of the mineral raw base of backfill materials, especially by the main inert filler that significantly increases the cost of backfilling works. However, in the operating conditions of other mines with a similar component proportion and a close rich mineral raw base, the mechanical activation of the binder material can be enough effective.

c) It has been determined that with an increase in the ratio of C_{bin}/C_{in} from 0.5 to 1.0, the costs of basic mixture variant and all mixture variants, where the mechanical activation was performed, are sharply reduced by 35-45%, and the difference between the costs of the most economical backfill mixture and the basic one is already 16.8%. With an increase in ratio of C_{bin}/C_{in} from 1.0 to 4.6, the difference in costs of the backfill mixture production in the considered compositions, where mechanical activation was performed, increases even more in a positive direction. But for the most economical backfill mixture, if compared to the basic one, it will be changed from 16.8 to 46.0%. This indicates that, if at any mine that uses CRF on the basis of ground smelter slags, waste of limestone and rock refuse, and the cost parameters of the binder material and inert filler are $C_{bin}/C_{in} > 1$, then the mechanical activation of the binder material is expedient.

d) To improve the expediency of applying the mechanical activation of the binder material, it is recommended to form a stope chamber with different strength along the height of the backfill massif based on the study of its stress state using numerical modelling. The obtained stress curves will make it possible to identify unstable areas of the backfill massif, which should be primarily strengthened, and in the rest areas of the backfill massif, where critical stresses are absent, a lower strength should be formed with a more economical CRF proportion, that is, a differential approach should be performed to the backfill massif construction.

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