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Research into cemented paste backfill properties and options for its application: Case study from a Kryvyi Rih Iron-ore Basin, Ukraine

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Abstract

Purpose. The purpose is to conduct experimental research on a set of properties of cemented paste backfill mass based on a number of natural-technogenic materials of the Kryvyi Rih Iron-ore Basin with the aim of its further use in technologies for restoring a heavily disturbed earth's surface by complex iron ore mining.

Methods. A comprehensive toolkit is used: X-ray fluorescence and X-ray diffraction analyses to study the chemical and mineralogical composition of the components, conductometer measurements of the electrical conductivity of the mixtures during their hardening, laboratory studies of the formulations of paste backfill mixtures and determination of their physical-mechanical characteristics using a laboratory hydraulic press, an analytical study to determine suitable regions for paste backfilling, taking into account the presence of technogenic cavities, tailings dumps and binder materials.

Findings. It has been found that a paste-like homogeneous state of the backfill mixture using iron ore beneficiation tailings from mining and processing plants of Ukraine is achieved at a solid part content of about 73-75%, which provides an optimal balance between its flowability and mechanical strength. A set of patterns of strength changes depending on the binder material dosage, solid part content and hardening period for paste backfill mixture based on pure cement and with different variations of alternative binder materials has been determined. The patterns have been revealed of the correlation between the paste backfill mixture strength and the electrical conductivity parameters.

Originality. A method for predicting the early and late strength of paste backfilling has been developed, based on the identified patterns between the electrical conductivity of the paste mixture, the time to reach its peak, and the strength at different stages of hardening. The knowledge and understanding of the physical-mechanical properties of cemented paste backfill mixture in the conditions of hardening under the influence of climatic environmental conditions have been further developed.

Practical implications. The conducted research on the properties of paste backfilling is useful for designing a technology for restoring heavily disturbed earth's surface, namely, backfilling of failure zones of the earth's surface from the influence of iron ore mines, backfilling of identified underground unfilled cavities of closed mines and mined-out spaces of closed quarries. A concept for implementing a paste backfilling in the western part of the city of Kryvyi Rih has been developed, which is expected to contribute to the environmental, economic and social development of the region.

Keywords: *cemented paste backfilling, beneficiation tailings, binder material, strength, electrical conductivity, failure zones, quarry cavities*

1. Introduction

The current stage of development of human civilization is characterized by rapid population growth and technological progress, leading to a significant increase in mining and consumption of mineral resources [1]-[3]. The mining industry, which ensures the functioning of key sectors of the economy – energy, metallurgy, construction, engineering, IT-technologies, healthcare and infrastructure – has a strong anthropogenic impact on the environment. Particularly destructive consequences are observed in the upper layer of the lithosphere due to the formation of open and underground technogenic cavities, which leads to soil degradation [4], [5], loss of land areas [6], [7], pollution of water resources and the atmosphere [8], [9], as well as to a decrease in biodiversity [10], [11].

The global scale of the problem is confirmed by numerous studies, according to which there are about 44929 objects of mining activity with a total area of more than 101.5 thousand km². Given the zones of influence, the area that is subject to anthropogenic changes can reach 50 million km² [12], [13]. Intensive subsoil development creates enormous volumes of waste: more than 150 billion tons of rock mass are mined annually, of which only 60-65 billion tons are useful components, 72 billion tons are waste rock and 13 billion tons are beneficiation tailings [14].

In the context of a significant negative environmental impact of mineral resource mining, the implementation of "green mining technologies", aimed at minimizing environmental impact and improving economic performance, is becoming increasingly important. Traditional methods of

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reclamation of open technogenic cavities created as a result of complex mining, such as filling with waste rock, have significant disadvantages. The filled-up rock backfill mass is characterized by high porosity, significant filtration capacity, and a tendency to self-compact under the action of gravity, which does not guarantee long-term geomechanical stability [15]-[18]. This does not guarantee blocking the development of shear processes in the failure zone and limits the possibility of further use of territories above the quarries for industrial, infrastructure, or social projects.

One of the key green technologies in underground mining is the backfilling of mined-out space of mines, which solves a number of important tasks: it facilitates the utilization of accumulated industrial waste [19]-[21], prevents dangerous development of the earth's surface deformations [22]-[24] and creates favorable geomechanical conditions for mining in difficult geological conditions [25]-[27]. However, due to the high economic costs, such backfilling operations are usually conducted only in cases where it is critically necessary, in particular, when mining under industrial or civil infrastructure facilities or with a high value of minerals. Today, the use of cemented paste backfilling is particularly widespread and is actively used in mining practices in countries such as China, Canada, Australia, the USA, and others [28]-[32]. This technology involves monolithic filling of cavities with a mixture of finely dispersed beneficiation tailings, binder material (such as cement, slag, fly ash) and water, which allows for the formation of a homogeneous and stable backfill mass. The main advantages of the paste backfilling include: low filtration coefficient, minimal shrinkage, environmentally friendly delivery of the mixture by pipeline transport, utilization of significant volumes of beneficiation tailings.

Under certain conditions, it may be considered appropriate to change the vector of using cemented paste backfilling from its direct purpose – backfilling the mined-out space of mines to filling technogenic cavities on the earth's surface arising as a result of complex mining of mineral resources. In the conditions of mining regions, where the earth's surface has undergone severe destruction and deformation, this will solve a range of environmental, economic, and social problems.Despite the successful use of cemented rock or cemented paste backfilling to fill underground cavities, its use to restore surface technogenic cavities (failure zones and quarry cavities) is still insufficiently studied, although certain aspects are partially mentioned by scientists [33]-[36].

A particularly critical situation has developed in the industrialized regions of Ukraine, in particular in the Kryvyi Rih Iron-ore Basin [37]-[41]. Large-scale iron ore mining has led to the formation of numerous underground and open technogenic cavities, failure zones, tailings dumps, and waste dumps. The disturbed land area exceeds 6000 hectares, and the total accumulated waste volume is about 10.7 billion tons [42]. The accumulated beneficiation tailings and waste rock cause intense dusting and polluting the atmosphere, thereby posing a threat to ecosystems and the health of the region's population. Given that the critical mining depth of iron ore mines has already been crossed and the active phase of landslides has been stabilized [43], [44], it is believed that the transition at operating mines from mining systems with rock caving and stope mining systems [45] to mining systems with backfilling of precisely underground cavities [46] (mining depths of 1300-1500 m) is ineffective, as it will no longer solve the existing complex geomechanical situation on the surface and will lead to significant economic costs for backfilling operations. However, it is possible to improve the geomechanical situation by using cemented paste backfilling of formed technogenic cavities directly from the earth's surface, which is a new direction combining environmental, technical, and economic aspects.

The implementation of this technology in the Kryvyi Rih Iron-ore Basin has significant potential to solve environmental and geotechnical problems in the region. Paste backfilling of technogenic cavities can improve the geomechanical state of heavily disturbed rock mass in the region, as well as utilize the accumulated beneficiation tailings, which are currently a source of technogenic load. Moreover, it can not only eliminate the technogenic hazard of mine failure zones, but also integrate the restored territories, for example, above the quarries, into the industrial and social development of the region. This is especially true for urbanized industrial centers such as Kryvyi Rih, where restored land can be used for infrastructure, industrial, and public projects.

The presented research is aimed at studying the physical-chemical and physical-mechanical properties of cemented paste backfill mixture based on iron ore beneficiation tailings using different types of binder materials during hardening in an open environment, which is conducted for the first time for the conditions of the Kryvyi Rih Iron-ore Basin and mining enterprises of Ukraine as a whole. In addition, an attempt is made to reasonably show the possibilities of using paste backfilling in technologies for restoring the disturbed earth's surface state in the conditions of the Kryvyi Rih Iron-ore Basin.

2. Materials and methods of research

2.1. Binder materials

Proceeding from global experience in implementing backfill technologies at world's leading mining enterprises, the following binder materials are widespread [47]-[50]: Portland cement, ground metallurgical slags, phosphogypsum, thermal power plant fly ash, ground limestone and other.

Based on the studied mineral and raw material base of potential sources of binder and inert backfill materials in the Kryvyi Rih Region, material samples are taken to study their chemical and mineralogical composition for their further use in the preparation of paste backfill mixtures. The following binder materials for cemented paste backfilling are used during the test: Portland cement of M500 grade from KryvyiRigCement PRJSC, blast-furnace granulated slag (BFGS) from PJSC ArcelorMittal, limestone from Zhovtokamianskyi quarry, and fly ash from a thermal power plant.

In order to use these materials as binder components of cemented paste backfilling, in addition to Portland cement, they are crushed to activate their hydration properties. This is due to the fact that the initial fractional composition of blast-furnace granulated slag in the dump is within 10...0 mm, quarry natural limestone – 20...0 mm (screenings), and fly ash in the ash-sludge dump – 0.3...0 mm. The crushed binder materials are hermetically packed in plastic bags before preparing the experimental backfill mixtures. Some physical characteristics of binder materials are shown in Table 1.

Table 1. Physical characteristics of binder materials

Binder material	Dispersion, mm (*after ball mill)	Bulk density, tons/m^3
Portland cement	91% (-0.08)	1.3
Blast-furnace granulated slag	68% (-0.08)*	1.51
Natural limestone	65% (-0.08)*	1.05
Dry fly ash	59% (-0.08)*	1.15

2.2. Iron ore beneficiation tailings

To prepare paste backfill mixtures, finely dispersed iron ore beneficiation tailings are used as the main and traditional inert material [51]-[53]. Samples of finely dispersed mature beneficiation tailings are taken directly from the drained alluviation maps of tailings dump of PJSC Northern Iron Ore Enrichment Works (Kryvyi Rih Basin) and Ferrexpo Poltava Mining (Kremenchuk Basin) (Fig. 1). The selected samples of beneficiation tailings have a lumpy structure, therefore, after drying, to bring them to a homogeneous structure, they are subjected to mechanical treatment using a metal roller.

(a)

(b)

Figure 1. Sampling of beneficiation tailings from alluviation maps of tailings dumps: (a) maps of tailings dumps of PJSC Northern Iron Ore Enrichment Works and Ferrexpo Poltava Mining (b)

Main physical characteristics of binder materials are given in Table 2. Aged tailings are classified as coarse (-20 μm < 35%).

Table 2. Physical characteristics of iron ore beneficiation tailings

Parameter	Particle size class, mm						
	+0.125	-0.125…+0.071	-0.071…+0.056	-0.056…+0.044	-0.044…+0.025	-0.025…+0.008	-0.008…0
Fraction content, %	6.3	20.9	25.1	16.4	13.7	10.3	7.3
Specific gravity, tons/m^3	2.8						
Bulk density, tons/m^3	1.65						

2.3. Determining the chemical and mineralogical composition of the backfill materials

Selected waste samples of natural-technogenic origin, considered as potential components for cemented paste backfilling, are examined in a finely dispersed state.

The chemical composition of the backfill material samples is determined by means of non-destructive X-ray fluorescence analysis using a Benchtop ElvaX spectrometer from Elvatech Company (Ukraine). The method is based on recording the characteristic X-ray radiation of the tested substance atoms, which occurs as a result of irradiation of the substance by an X-ray tube. Such a component as fly ash is subjected to calcination in a muffle furnace to a temperature of 850°C to determine the volatile matter content and to study the ash fraction.

Qualitative and quantitative mineralogical composition of paste backfill components is studied by means of X-ray phase analysis using a DRON-3 X-ray diffractometer in monochromatic Co-Kα radiation (λ = 1.7902 A). The compounds (phases) are identified by comparing the interplanar distances (d, A) and relative intensities ($I_{otn} - I / I_0$) of the experimental curve with data from the PCPDFWIN electronic file. Surveying is carried out at angles of 10-90°. The structural analysis is performed with a step of 0.01° and a duration of 5 s. For quantitative analysis, the ratio of peak intensities inherent in each phase is used. Comparing the intensity of the main diffraction peaks of each phase with the total intensity of all peaks allows estimating the amount of a particular phase in the sample and is a simple, however, practical method.

The type of samples tested and the laboratory equipment used in the research is illustrated in Figure 2.

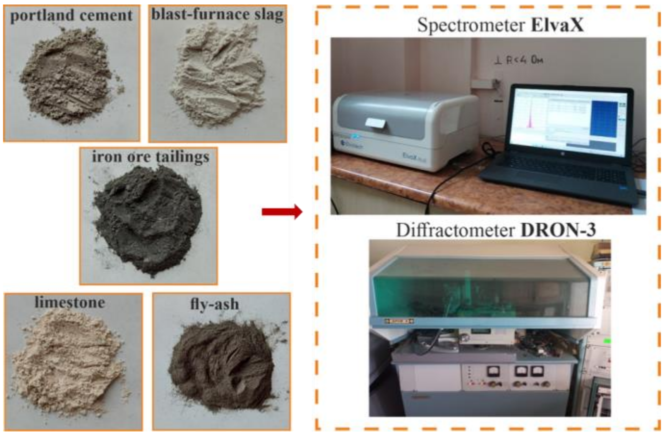

Figure 2. Backfill materials and laboratory equipment during research on chemical and mineralogical composition

2.4. Research on paste backfill mixtures

2.4.1. Preparation of paste backfill mixtures

First of all, paste backfill mixtures based on Portland cement, which is the main binder material in the world practice of paste backfilling, are prepared and further studied. Portland cement-based paste backfill mixtures and their physical-mechanical properties are a kind of standard that should be used when trying to replace part of the cement in backfill mixtures with alternative binder materials.

During the tests, formulations of paste backfill mixtures are prepared with varying cement content of 3, 6, and 9% of the solid part of the beneficiation tailings in the dry state. The solid part content (dry beneficiation tailings + dry binder material) in the backfill mixtures is 70, 75, 80%, according to the experience of using paste backfilling [54]-[56], and water 30, 25, 20%, respectively. The water-cement ratio in the backfill mixtures is as follows 1:11; 1:5.5; 1:3.7, respectively. To optimize the composition of the paste backfill mixture, the possibility of replacing expensive cement with alternative binder materials is explored. To do this, after substantiating the rational content of the binder material, that is, after selecting the binder material content and rational consistency of the paste backfill mixture in terms of solid part content, cement is replaced with crushed blast-furnace granulated slag in the amount of 30, 50, 70 and 100%. At the ratio of the combined binder material, cement-slag 30:70, an attempt is made to replace part of the slag (30%) with crushed natural limestone and dry fly ash by preparing separate paste backfill mixtures.

The beneficiation tailings are dried in a drying cabinet of the SNOL 58/350 type to a dry pulverized state. Next, the paste backfill components are weighed according to the planned formulations using a laboratory balance WLC 20/C/1, poured into a container, mixed in a dry state with the subsequent addition of water (Fig. 3). Water-wet backfill components are mixed with a laboratory mixer for 5-7 minutes until a paste-like consistency is achieved.

(a) (b) (c) (d)

Figure 3. The process of preparing paste backfill mixture: (a), (b), (c) weighing the required amount of beneficiation tailings, cement, and additional binder material; (d) filling the mixture of components with water

Paste backfill mixtures prepared are poured into three-nested metal molds 3FC-70 with a cell size of 70×70×70 mm for further manufacturing of cubic samples and testing them for strength at a hardening period of 3, 7, 14, 28 and 56 days (Fig. 4). For each hardening period, 3 cubic samples of the corresponding experimental composition are prepared. A total of more 100 cubic samples have been made. The average strength value is taken for 3 samples, provided that the strength does not differ by more than 10%.

Figure 4. Paste backfill mixtures placed in metal molds 3FC-70

The backfill mixtures are prepared in a volume slightly larger than that required for pouring the 3FC-70 mold due to the need to study the kinetics of the hydration process. In order to simulate the conditions for filling surface technogenic cavities, such as quarry cavities or failure zones, which are located in an open space under the influence of climatic conditions, the backfill samples after disassembling the molds are kept in the ambient environment at a temperature of 20-25°C and air humidity of 40-50% (Fig. 5).

Figure 5. Hardening of cubic paste backfill mixture samples in the ambient environment

After reaching the hardening period set by the experimental program, the cubic samples are to be tested for physical-mechanical properties.

2.4.2. Slump test

To obtain primary information on the flowability of paste backfill mixtures, a simple but effective method of slump cone is widely used in the practice of backfilling operations and in the construction industry [57]-[59], which consists in measuring the decrease in the height of the mixture accumulated in a measuring vessel (cone). Typically, a standard Abrams cone is used, with dimensions of 300 mm in height, 100 mm is the upper base diameter, and 200 mm is the lower base diameter. In the case when there is a need to prepare a significant amount of paste backfill mixtures and in order to save the consumption of backfill materials, this method can be modernized by creating a mini-cone with the following dimensions: height – 300 mm, upper base diameter – 100 mm and lower base diameter – 200 mm.

It has been proven that experimental studies using a mini-cone correlate with tests of the Abrams cone. To test experimental paste backfill mixtures using a slump cone, a metal mini-cone with the specified geometric parameters has been made (Fig. 6).

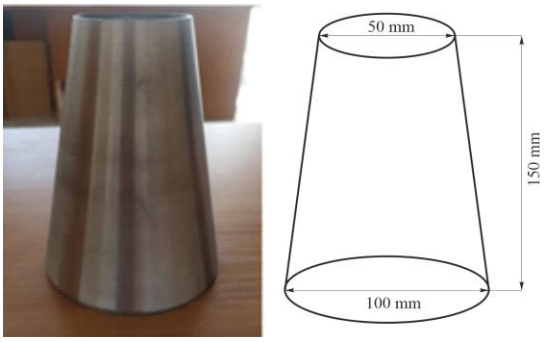

Figure 6. A metal mini-cone made to study the slump value of the mixture

The algorithm for studying paste backfill mixtures on slump cone is as follows (Fig. 7). A paste backfill mixture of a certain consistency is prepared. To test the paste mixture for slump, the cone is placed on a flat surface and filled with the mixture to the top edge with light compaction. Then the cone rises vertically in 2-3 seconds, after which the mixture settles or spreads. The difference between the initial cone height and the height of the truncated mini-cone is measured, which characterizes the value of the mixture slump. Additionally, the angle and diameter of the mixture spreading are measured, which are important parameters when filling the mined-out space of the quarry and the mine failure zone.

The results of measurements of the slump value of experimental paste backfill mixtures when using the mini-cone device are explained as follows:

– slump exceeds 120 mm (80% of the cone height) – the backfill mixture is too liquid in consistency, characterized by low viscosity and is transported through pipelines with minimal pressure loss; however, it can lead to stratification, insufficient load-bearing capacity and a significant decrease in strength and slump after hardening;

– slump is in the range of 50-100 mm (33-67% of the cone height) – the backfill mixture is homogeneous, has optimal transportability, workability and is not prone to sedimentation (particle segregation); this is a favorable range for most backfilling operations, which ensures efficient filling and, after hardening, provides high strength and minimal slump;

– slump is less than 50 mm (less than 33% of the cone height) – the backfill mixture is too dense, of high viscosity and insufficiently fluid, which can complicate its transportation through the pipeline due to increased pressure and uniform distribution in the mined-out space.

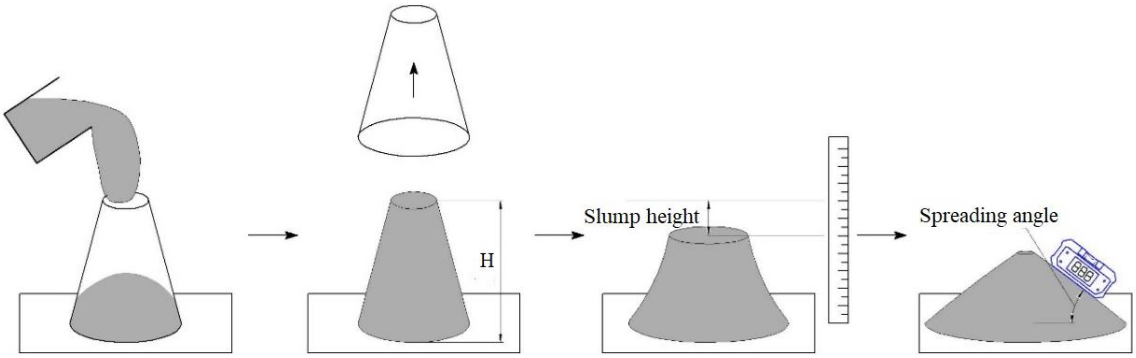

Figure 7. Sequence of stages of paste backfill mixture testing for slump value

The slump value of experimental paste backfill mixtures with a solid part content of 70, 75, and 80% is tested. It is of considerable scientific value to determine at what concentration of the solid part in the mixture, mostly consisting of finely dispersed iron ore tailings from Ukrainian mining and processing plants, the paste-like consistency and the most optimal slump value for the efficiency of the pipeline transportation process are achieved.

2.5. Hydration kinetics study

To study the hydration kinetics process of binder materials in paste backfill mixtures, an electrical conductivity (EC) parameter is used, measured by means of a BT-761 Soil Conductivity Meter (Soil Tester) in the range of 0-19.9 mS/cm.

The device is placed in a magnetic stand, the electrode of which is submerged in a container with the tested paste backfill mixture (Fig. 8). The electrical conductivity value is studied over time, first by adding the main binder material (Portland cement) at its content of 3, 6 and 9%, as well as with various combinations of other binder materials, according to the methodology.

Figure 8. Monitoring of electrical conductivity values of the paste backfill mixture using a BT-761 conductivity meter

The change in the electrical conductivity (EC) value of the mixture is recorded every 0.5-1 hour until it decreases. The analysis of hydration kinetics is based on the study of the nature of the EC change and peak values over time, which characterizes the hardening process as a whole.

2.6. Physical-mechanical properties

A manual hydraulic press JG-212 (China) with the ability to generate a maximum pressure in the hydraulic system of up to 25 MPa is used to study the compressive strength of hardened paste backfill mixture samples (Fig. 9a), which is also suitable in size for testing samples measuring 70×70×70 mm. Given the design peculiarities of the hydraulic press, it has been found that the limit for determining the compressive strength of paste backfill samples is in the range of 0-10 MPa, which is quite sufficient for this backfill mixture type.

(a)

(b)

Figure 9. Hydraulic press JG-212 for testing paste backfill samples for compressive strength: (a) a view of the press with a placed cubic paste backfill sample before testing; (b) measuring the geometric dimensions of samples and the shrinkage value under load

The principle of the press operation is that when the mechanical pump lever is pressed, hydraulic oil moves the piston, which exerts pressure on the placed metal platform with the sample. During the strength tests, the pressure value in the hydraulic system is recorded when the sample is destroyed and the pressure increase stops due to the disappearance of resistance. To determine the direct compressive strength of the backfill sample, the force acting on the platform with the sample is first calculated based on the recorded pressure and piston area. Using the load force value and the measured cross-sectional area of the sample, the compressive strength is calculated. Before testing the samples for strength, the exact dimensions of the sides of the cubic backfill samples are recorded using an electronic caliper, and during the test, the reduction in linear dimensions under load is recorded (Fig. 9b).

To study the most important mechanical property of a monolithic paste backfill mixture – the strain modulus *E*, which determines the resistance of the backfill mass to shrinkage, the following Formula is used [60]:

$$E = \frac{\Delta F \cdot h_1}{S \cdot \Delta h}, \quad (1)$$

where:

$\Delta F = F_2 - F_1$ – is the difference between final and initial load on the sample, kN;

F_1 – is the initial load recorded on the device at the beginning of the test, kN;

F_2 – is the load at the end of the test, recorded on the device, kN;

$\Delta h = h_2 - h_1$ – is the difference between the final and initial height of the sample, mm;

S – is the cross-sectional area of the sample, mm^2.

The difference between the final and initial heights of the paste backfill sample is determined using a digital caliper. The obtained experimental dataset of hydration kinetics and strength characteristics of the backfill mixtures is analyzed, systematized, and processed using Microsoft Excel to determine the mathematical nature of the correlation dependences.

3. Research results and discussion

3.1. Chemical and mineralogical composition of the backfill materials

The study of the chemical and mineralogical composition of backfill materials for the formation of backfill masses is of significant importance, which consists in identifying and understanding the types of minerals involved in hydration processes, the hardening mechanism and premature prevention of negative chemical reactions, such as, for example, sulfate attack, which leads to the destruction of a monolithic paste backfill mass. The results of determining the chemical composition of these components are shown in Table 3.

Table 3. Chemical composition of the tested backfill materials

Material	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	K_2O	SO_3	MnO	TiO_2	Others
Portland cement	31.3	59.7	5.0	0.6	1.5	–	0.5	0.05	0.12	1.23
Beneficiation tailings 1	71.5	2.35	0.99	20.8	3.7	0.34	0.03	0.02	0.015	0.25
Beneficiation tailings 2	68	2.5	1.22	23.9	3.7	0.3	0.08	0.07	0.03	0.2
Blast-furnace granulated slag	39.1	44.2	6.55	0.45	6.2	0.5	0.74	0.3	0.19	1.77
Fly ash	50.5	3.1	21.1	7.76	1.3	2.3	0.69	0.05	1.06	11.55
Limestone	5.1	53.7	2.21	1.4	0.4	–	–	–	–	37.11

Analysis of the results in Table 3 shows that Portland cement has a sufficiently high-quality chemical composition, characterized by a high content of calcium oxide (59.7%) and an optimal proportion of silica (31.3%), which contributes to the formation of a strong mass structure. The moderate aluminum oxide content (5.0%) accelerates the hardening process, while the low iron oxide level (0.6%) minimizes undesirable effects. The content of MgO (1.5%) and SO_3 (0.5%) is within normal range, which prevents possible expansion and fracture formation. Finely dispersed iron ore beneficiation tailings are mostly composed of quartz (71.5%) and iron-containing minerals (20.8%), which is quite typical for this type of waste. Most of the iron minerals are recovered during the beneficiation process, while silicate rocks and some non-recovered iron remain in the tailings. The presence of insignificant concentrations of calcium, aluminum, and magnesium oxides indicates the presence of carbonate, aluminosilicate rocks and magnesium silicates. The main chemical composition of blast-furnace granulated slag is represented by 4 oxides: calcium (44.2%), silicon (39.1%), aluminum (6.55%) and magnesium (6.2%). Based on the chemical slag composition, its important properties determining hydraulic activity are identified: basicity modulus – 1.1; activity modulus – 0.17; quality factor – 1.45. The studied blast-furnace granulated slag belongs to the main ones and has an average hydraulic activity in terms of activity modulus and quality factor. Slag of this quality can hardly be used as the main binder material in paste backfilling, but it can replace a certain part of expensive Portland cement.

Chemical analysis of fly ash shows that the main chemical substances are aluminosilicates, since the content of silicon oxide and aluminum oxide is 50.5 and 21.1%, respectively. It is also noted that the content of iron-containing minerals is 7.76%, which is contained in the rocks that constitute the ash part of coal when burned in thermal power plants. The fly ash sample calcination shows that there is a 11.55% mass loss, which is associated with the content of fuel mass, that is, unburned coal. The tested fly ash belongs more to class F and has pozzolanic properties that can improve certain physical-mechanical properties of the paste backfill mass, but in order to increase its activity, it is probably necessary to crush it.

The chemical composition of natural limestone is represented by 53.7% of calcium oxide, which indicates its carbonate nature. Given the low magnesium oxide content (0.4%), it is probably that limestone consists of calcite. With a calcium oxide content of 53.7%, the calcite content ($CaCO_3$) in limestone is 95.8%. Similarly to fly ash, limestone screenings, which is a waste in the quarry, can be used as a mineral additive capable of replacing a cement share, only in a crushed state.

The research conducted (Table 3) shows another important aspect: the similarity of the chemical composition of iron ore beneficiation tailings from Ferrexpo Poltava Mining and PJSC Northern Iron Ore Enrichment Works in the Kry-vyi Rih Region. Given that a larger number of tailings samples, taken for research specifically from Ferrexpo Poltava Mining, can be used in experiments to prepare paste backfill mixtures, which will help to model and reproduce the conditions of the Kryvyi Rih Region. The mineralogical composition of all the materials sampled is examined using X-ray diffraction analysis. However, Figure 10 illustrates the X-ray diffraction patterns of some of the backfill materials, namely iron ore beneficiation tailings and blast-furnace granulated slag.

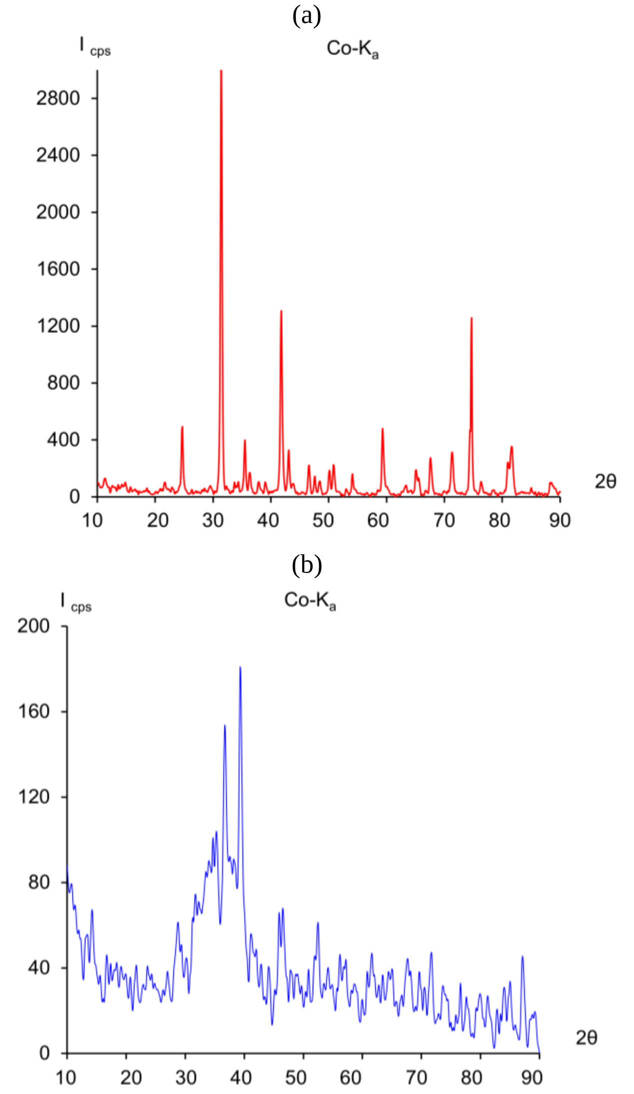

Figure 10. X-ray diffraction patterns of iron ore beneficiation tailings (a) and blast-furnace granulated slag (b)

X-ray diffraction pattern of the Portland cement sample is not performed, since the mineralogical composition of this technogenic material is usually known to the manufacturer. However, focusing on the chemical composition (Table 3), it is possible to assume that Portland cement includes alite (about 60%), belite (21%), and the remaining 19% is represented by tricalcium aluminate and tetracalcium aluminoferrite. Based on the analysis of the obtained X-ray diffraction pattern data (Fig. 10), it has been revealed that the composition of finely dispersed tailings from Ferrexpo Poltava Mining includes quartz (65-70%), hematite and magnetite (13-15%), carbonate rocks (6-9%), and other unknown pha-ses. Blast-furnace granulated slag consists of a crystalline and amorphous structure, the latter occupying 40%, which is typical for rapid cooling of slag. The crystalline structure consists of helenite (42%), rankinite (about 28%), and melilite (15%). Natural limestone is 96% calcite, and dry fly ash is 95% aluminosilicates with admixtures of magnesium and iron, which is probably the mineral cordierite. Dump hard rocks consist of 58% quartz, 27% feldspar or orthoclase, muscovite (5%) and calcite (5%), while the remaining 5% is diabase, plagioclase and other minerals.

3.2. Research on the rational consistency of a paste backfill mixture

The solid part and water content in the paste backfill mixture is a key parameter that determines its rheological properties, transportability and final strength. The balance between the solid phase and water provides the necessary flowability of the mixture for efficient transportation through the pipeline and sufficient strength to form a stable backfill mass, minimizing slump and ensuring the mass durability.

The research is aimed at achieving a balance between manufacturability, transportability, and cost-effectiveness of the paste backfill mixture. For this purpose, the test for slump is performed with an average cement dosage of 6% of the total solid part content. As a result of the paste backfill mixture preparation with different solid part content of 70, 75 and 80%, according to the experience of backfilling operations, where the content on average varies at the level of 70-80%, different types of their consistency are recorded (Fig. 11.)

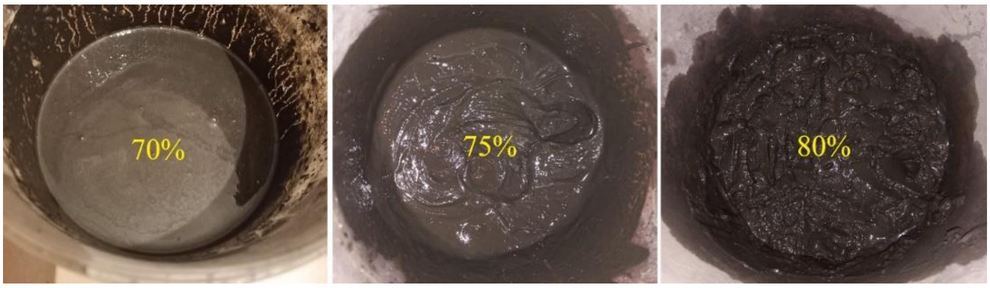

Figure 11. Consistency of backfill mixtures with different solid part content (70, 75, and 80%)

At a content of 70%, the consistency is too liquid, which on the one hand ensures high transportability due to low viscosity and high flowability, but on the other hand, it is predicted to achieve a higher hardening rate, low strength due to the significant amount of water and probably significant slump. With a solid part content of 75%, an optimal paste-like mixture with moderate flowability and transportability is achieved. The mixture with the addition of a binder material provides high strength after hardening with minimal slump. With a solid part content of 80%, the consistency is thick, lumpy and inactive. Transportability is low due to high viscosity and requires significant energy consumption and plasticizers for transportation. There is a risk of particle sedimentation and pipeline blockage due to insufficient flow rate. Strength is predicted to be high due to minimal water content, but the risk of technological difficulties increases.

Figure 12 illustrates the slump measurement using a mini-cone for backfill mixtures with different solid matter contents (70, 75 and 80%), which, as in the photo above, interpret the physical essence of the consistency with a change in the solid part. With a solid part content of 70%, the mixture shows maximum slump due to high flowability, indicating its ease of transportation, but possible insufficient strength. At 75%, the slump decreases, indicating an optimal consistency of the mixture and providing a balance between plasticity and strength.

(a) (b) (c)

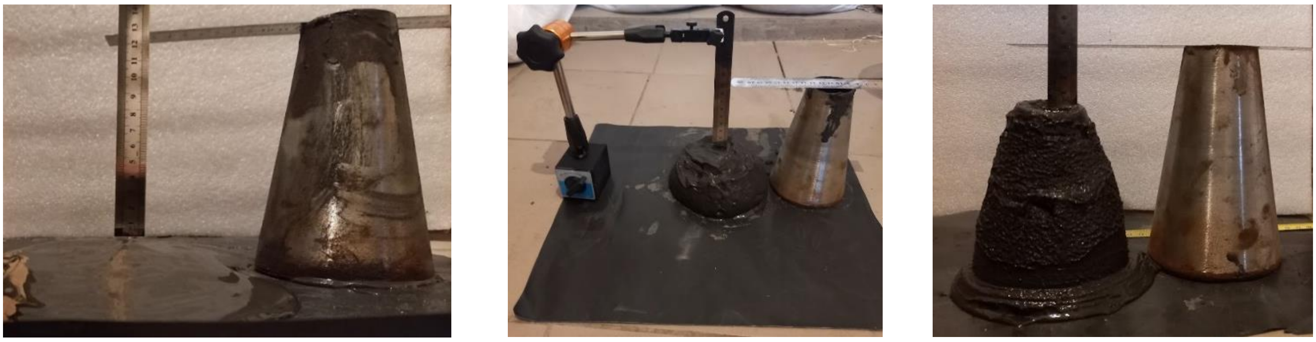

Figure 12. Research on the slump value of backfill mixtures based on beneficiation tailings at different solid part content (70, 75, and 80%)

A mixture with 80% solid part has minimal slump, while maintaining a cone shape, indicating its high density and strength, but limited transportability. It has been experimentally confirmed, as well as by previous researchers, that measuring the mixture slump makes it possible to primarily assess its suitability for transportation. The mixture spreading parameters are given in Table 4.

Based on the experimental data obtained, the dependence of the change in the slump value of the mixture on the solid part content has been determined (Fig. 13). It has been found that with an increase in the solid part content from 70 to 80%, the cone slump decreases significantly, indicating an increase in viscosity and a decrease in the flowability of the mixture.

Table 4. Parameters of paste backfill mixture spreading at different solid part content

Solid part content, %	Slump value, cm	Pouring diameter, cm	Spreading angle, deg
70	13,1	19.0	11-13
75	8.0	14.0	57-60
80	4.0	12.0	75-77

Exponential approximation demonstrates a high level of correlation between the parameters. Optimal cone slump is achieved at a solid part content of about 75%, which is about 8-10 cm. A further increase in the solid part content to 80% leads to an excessive decrease in flowability, which can greatly complicate the mixture transportation.

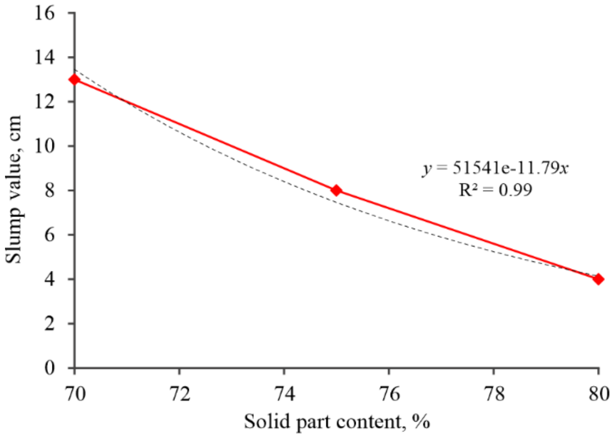

Figure 13. Dependence of the paste mixture slump value on the solid part content

It has been revealed that a paste-like homogeneous state of the backfill mixture using iron ore beneficiation tailings from Ukrainian mining and processing plants is achieved at a solid part content of about 73-75%, which provides an optimal balance between its flowability and mechanical strength when adding binder material. At this level of solid part content, the mixture has sufficient plasticity to uniformly fill cavities and be efficiently transported through the pipeline, avoiding the risk of particle sedimentation (segregation). The paste-like state also depends on the granulometric composition of the tailings, and the experience of foreign scientists has shown optimal values at both 70 and 77%.

In further research, the optimal solid part content of 75% is assumed and various paste backfill mixtures both based on cement and alternative binder materials are developed.

3.3. Research on the properties of paste backfill mixtures based on pure cement as a traditional binder material

Understanding the kinetics of hydration and hardening processes of the paste backfill mixture is important, since it provides an opportunity to predict the dynamics of the process of gaining the backfill mass strength in time and determine the optimal hardening conditions, as well as to select the mixture composition to achieve the required mechanical characteristics and durability, taking into account economic requirements.

To study the kinetics of the hydration process, it is possible to use the property of electrical conductivity (EC), which can be measured immediately from the moment of preparation of a fresh paste backfill mixture until its hardening. EC is one of the important properties of materials that characterizes their ability to conduct electric current. Previous research has revealed that the EC index can be used to assess the intensity and evolution of cement hydration and microstructural transformations in paste backfill samples [61]-[63]. Electrical conductivity reflects the concentration of ions in a mixture, which is associated with the dissolution and interaction of mineral components, such as cement, fine tailings particles, and water, and is provided by their movement. In the hydration process, dissolved ions gradually become fewer, as they participate in the formation of new solid crystalline phases, and the EC value gradually decreases. Consequently, the electrical conductivity of a mixture depends on the number (concentration) of ions and their mobility – the more ions and the higher their mobility, the higher is the conductivity. By monitoring the change in EC over time, it is possible to estimate the rate and stages of hydration, which can help to predict the moment when the mixture reaches a certain level of strength, as well as to determine how effectively the hardening and structure formation of the backfill mass occurs.

Today, in mines and quarries abroad, the most common type of binder material as part of cemented paste backfilling is cement, the content of which, due to its higher cost, is tried to be reduced while maintaining acceptable mechanical backfill mass characteristics, provided that there is a local mineral and raw material base of alternative binder materials. Nevertheless, cement is the main binder material and when testing new formulations of backfill mixtures, it is important to have a comparative characteristic of properties with backfill mixtures based on pure cement. In the context of new research on cemented paste backfill mixture based on iron ore beneficiation tailings from mining and processing plants, the priority task of developing optimal backfill mixtures should also be to study their properties based on pure cement.

As a result of performing a series of experimental measurements of the electrical conductivity values of prepared backfill mixtures over time, with different cement content, graphs of changes in their dynamics have been obtained, illustrated in Figure 14. Analysis of this Figure indicates the wave-like nature of the binder material hydration and leads to a number of important scientific results. Thus, at the initial stage (up to 400 hours), there is a gradual increase in electrical conductivity for all mixtures, which can be explained by the active cement hydration phase, with a higher intensity at a content of 6 and 9%. During this period, the concentration of ions in the solution increases due to the cement dissolution of and the formation of hydrate phases. For each paste mixture, the maximum EC value is reached at different time points.

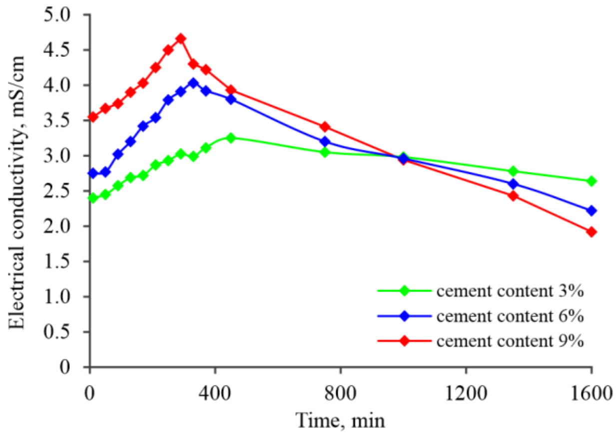

Figure 14. Dynamics of changes in electrical conductivity value over time at different cement content in the paste backfill mixture

The mixture with 9% binder material content reaches the highest peak of 4.65 mS/cm after ≈ 300 hours; with 6%, the value of 4.03 mS/cm is reached after ≈ 370 hours; and with 3%, the value of 3.25 mS/cm – after ≈ 460 hours, respectively. Also, as can be seen from the figure, there is a difference in peak time between the 9 and 3% cement mixtures, which is about 160 minutes, indicating about 35% difference in the rate of hydration onset between them and a 19% difference between 9 and 6%.

At the determined optimal value of the solid part content of 75%, paste backfill mixtures are prepared with varying cement dosage of 3, 6 and 9% of the total solid part. Portland cement is the main binder material with high hydraulic activity and is the most commonly used in foreign practice of backfilling operations and is essentially a standard, but expensive material. Cubic samples of mixtures are made and tested at 3, 7, 14, 28 and 56 days of hardening with different Portland cement dosages (Fig. 15).

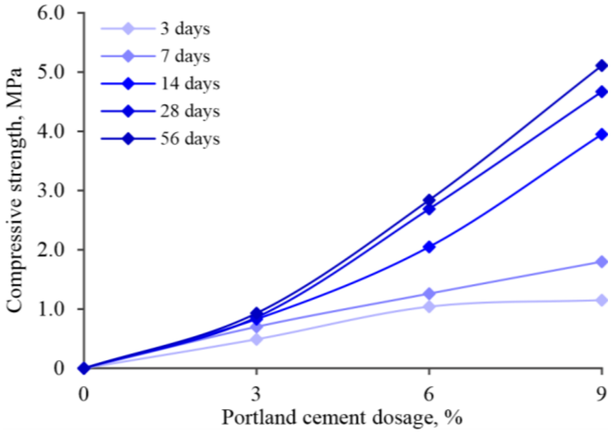

Figure 15. Dependences of changes in the compressive strength of the backfill mixtures at different Portland cement dosages

Figure 15 analysis shows that an increase in the cement dosage from 3 to 9% with total solid part content in the mixture of 75% significantly increases the paste backfill mass strength at all stages of hardening. At the early stages, the strength increases from 0.5 to 0.9 MPa (80% increase) in 3 days, and from 1.0 to 1.8 MPa (80% increase) on the 7^{th} day. These values indicate the initial active hydration of cement, and increasing the cement dosage accelerates the formation of the primary structure. In medium terms, the strength increases from 1.5 to 3.0 MPa (100% increase) in 14 days, and from 2.2 to 4.5 MPa (105% increase) in 28 days. This period is characterized by the active formation of a dense structure due to the hydration of a large share of cement. At the later stages, the strength reaches maximum values: from 2.5 to 6.0 MPa (140% increase), which is due to the completion of hydration processes and compaction of the mixture structure. These results demonstrate that cement dosage has a direct proportional effect on strength, especially at the later stages of hardening due to active hydration processes and the formation of a denser backfill mass structure.

To identify the influence of the total solid part content in the paste backfill mixture on the value of change in the strength characteristic, their relationship is studied, illustrated in Figure 16.

The dependences illustrate the influence of the solid part concentration on the final strength of backfilling. It has been determined that with an increase in the solid part content from 70 to 80%, the paste backfill mass strength increases at all stages of hardening: after 3-7 days it increases by 15-30%, after 14-28 days – by 50-70%, and after 56 days it reaches 100%. There is a clear tendency that at the later stages of hardening (28-56 days) the influence of the solid part content becomes more evident.

To identify the influence of the hardening period of paste backfill mixture on the value of change in the strength characteristic, their relationship is studied, as illustrated in Figure 17.

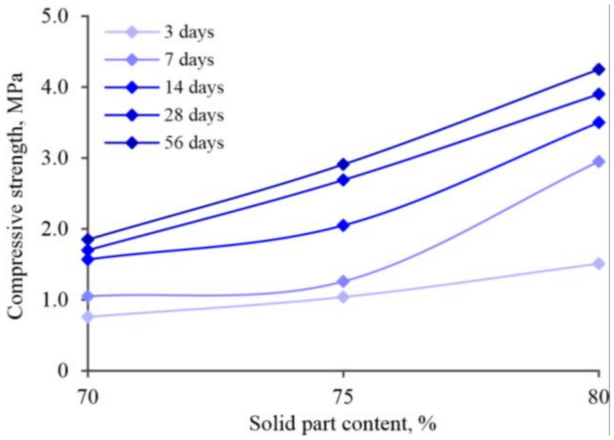

Figure 16. Dependence of backfill mixture strength on the solid part content at a fixed hardening period

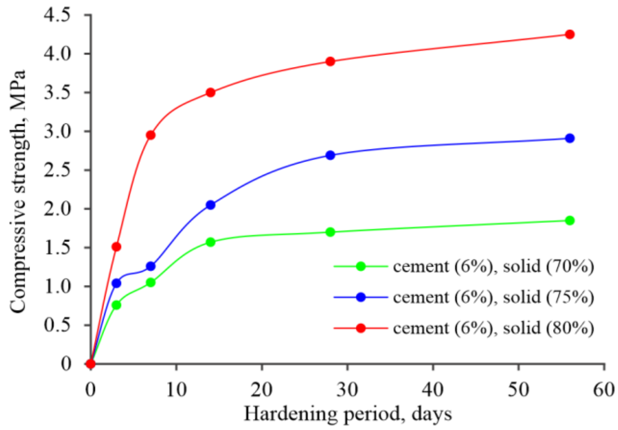

Figure 17. Dependence of strength on hardening period at a fixed solid part concentration

The dependences illustrate the rate of strength gain with increasing solid part content. The strength characteristics of a paste backfill mass are significantly dependent on the solid part content. When the solid part content increases from 70 to 80%, the compressive strength increases more than 2 times in 56 days (for example, from 1.5 to 4 MPa). For 75% of solid part content, the strength increases by 25-30% compared to 70%, and for 80% – by 30-40% compared to 75%. The higher solid part content helps to compact the structure and reduce the porosity of the mixture, which increases the final strength. However, this can also limit the ease of transportation and placing of the mixture.

Thus, the graph in Figure 16 gives an understanding of the dynamics of strength gain, and Figure 17 shows the influence of the hard part content on the final characteristics. Both graphs complement each other, allowing for a comprehensive assessment of the strength parameters of a paste backfill mass. In further research on optimizing the composition and replacing part of the expensive cement, a component composition of 6% binder material and 75% total solid part is chosen as the basic one, as it provides acceptable strength, optimal technological properties of the mixture and positive strength dynamics.

3.4. Research on the properties of paste backfill mixture with possibility to replace a cement share with alternative materials

In order to be able to replace expensive cement, paste backfill mixtures are prepared with varying content of binder material, the closest in terms of hydraulic activity of all available materials – blast-furnace granulated slag. In all component compositions, the binder material content is 6% of the solid part (dry mass of beneficiation tailings), which is 75%, and the rest is water. The cement proportion is gradually replaced with blast-furnace granulated slag in steps of 30, 50, and 70%. With a ratio of 30% cement to 70% slag, an attempt is made to add crushed limestone and crushed fly ash. Thus, the combined binder material is 30, 50, 20%.

Before pouring the cubic samples, all the backfill mixtures are tested for the property of electrical conductivity. Additionally, the samples are prepared with a cement/granulated slag ratio of 10/90. The research results are presented in Table 5.

Table 5. Characteristics of the electrical conductivity of mixtures

Mixture composition	EC value, mS/cm	Time to peak value, min
C-BFGS-70/30	3.85	240
C-BFGS -50/50	3.2	300
C-BFGS -30/70	2.5	360
C-BFGS -10/90	1.8	720
BFGS -100	1.1	900
C-BFGS-L-30-50-20	2.4	350
C-BFGS-DA-30-50-20	2.3	420

Table 5 data demonstrate that the electrical conductivity of the mixture and the time to its peak value depend on the type of binder material. Mixtures with a high content of cement and blast-furnace granulated slag show high electrical conductivity and shorter time to peak, indicating accelerated hydration compared to other formulations.

Large batches of cubic samples are manufactured (Fig. 18) and tested for compression. As a result of testing the backfill mixture samples for strength, the moments of fracture formation and continuity of the samples are recorded, at which the hydraulic pressure in the press no longer increases. The moments of destruction of samples are illustrated in Figure 19.

As a result of processing the experimental data of the strength values of the paste backfill mixture samples at different combinations of binder material during 3, 7, 14, 28 and 56 days of hardening, the corresponding dependences have been obtained, presented in Figure 20. Analysis of the obtained dependences (Fig. 20) indicates that when using 6% binder material and 75% solid part in paste backfill mixtures, replacing cement with blast-furnace granulated slag (BFGS) in a proportion of up to 70% leads to a gradual decrease in strength.

(a) (b)

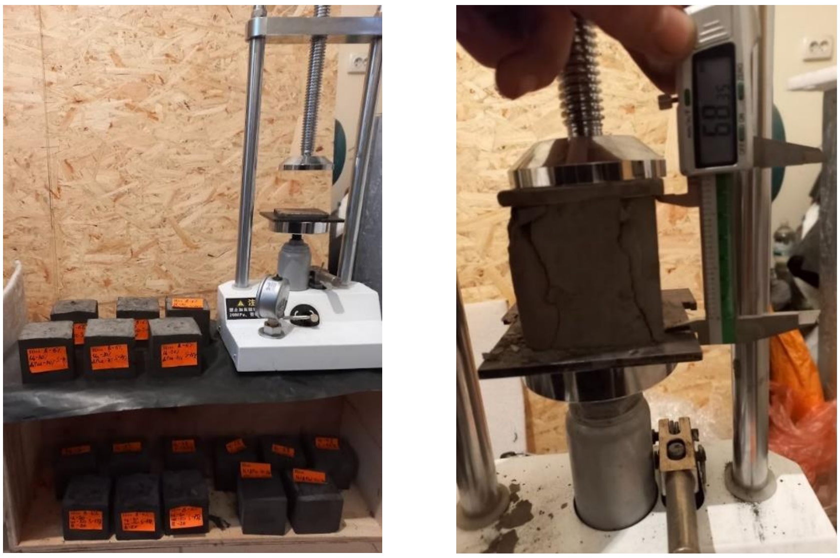

Figure 18. Research batch of cubic paste backfill mixture samples of different component composition for the next test: (a) for compression; (b) monitoring of sample deformations

Figure 19. Illustration of compression testing of a cubic paste backfill mixture samples

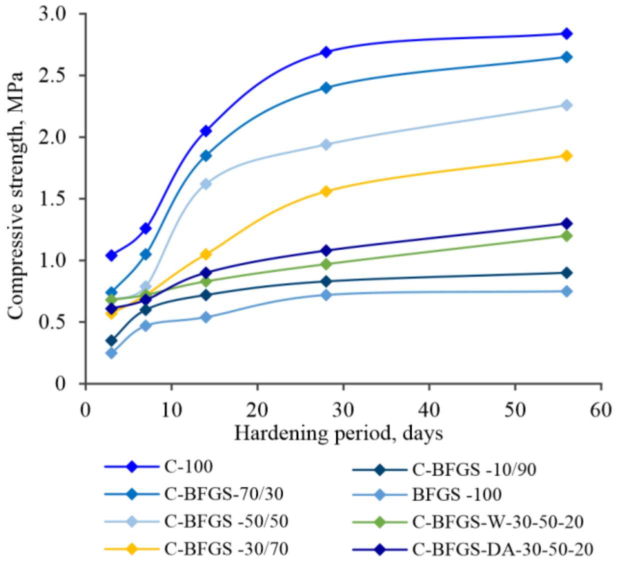

Figure 20. Dependences of the change in strength characteristics on the hardening period at different binder material variations (solid part content is 75%)

The best strength results are achieved with a cement/slag ratio of 70/30 without a significant decrease in strength. However, a mixture with a ratio of 30/70 demonstrates acceptable strength of up to 28-56 days (about 1.5-2.5 MPa), which may be sufficient for filling failure zones or quarry cavities and subsequent construction reclamation. For economic reasons, a 30/70 composition with a dominant slag share can be recommended, since a balance is achieved between strength characteristics, reduced cement costs and the environmental benefits of using metallurgical waste. The introduction of additional components, such as limestone and dry ash, shows no significant advantages, reaching a strength of about 1.0 MPa on day 56, which is explained by their lower activity in hydration processes compared to cement and slag.

To determine the deformation characteristics of the proposed cemented paste backfill mixture composition C/BFGS 30/70, changes in the linear dimensions of cubic samples under compression, namely changes in the height of the sample, are noted. Based on the formula given in the methodology, the strain modulus of the backfill mixture and the corresponding dependence have been determined (Fig. 21). The graph analysis in Figure 21 shows the change in the strain modulus of the paste backfill mixture over time, where 70% of the cement is replaced by crushed blast-furnace granulated slag.

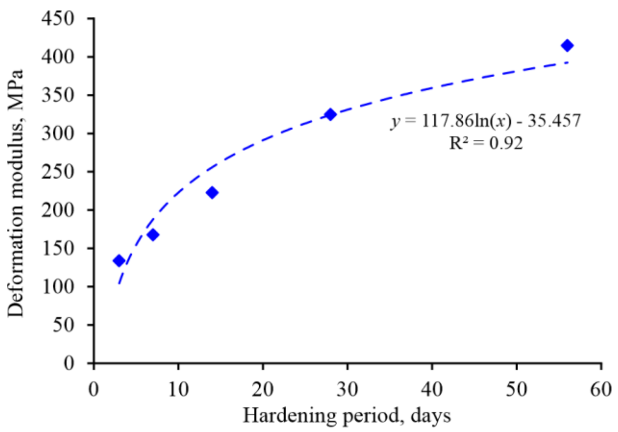

Figure 21. Pattern of change in the strain modulus over time for a paste backfill mixture C – BFGS of 30/70 ratio

The graph demonstrates a logarithmic dependence between the strain modulus and the hardening time, which is confirmed by sufficient reliability of the approximation. After 56 days, the strain modulus reaches about 400 MPa and continues to increase slowly. It is predicted to reach an elasticity modulus of 600-700 MPa within a few years. The specified component composition is promising for backfilling technogenic cavities, such as failure zones, or for filling a quarry or failure zone with subsequent construction reclamation. The use of 70% slag reduces the cement share, providing favorable mechanical, environmental and economic benefits.

In general, the paste backfill mixture is presented in the following percentage ratio: 4.5% of binder material, 70.5% of finely dispersed iron ore beneficiation tailings, 25% of water, and binder material is combined (30% of cement and 70% of blast-furnace granulated slag).

3.5. Relationship between electrical conductivity and paste backfill mass strength

There is a theory that proves that the electrical conductivity value of the mixture during its hardening process can serve as an indicator of the backfill mass strength. For this purpose, an attempt is made to identify a correlation between the parameters of early and late strength of hardened paste backfill mass samples and the peak value of the electrical conductivity of the mixtures and the time of its achievement, which is shown in Figures 22 and 23.

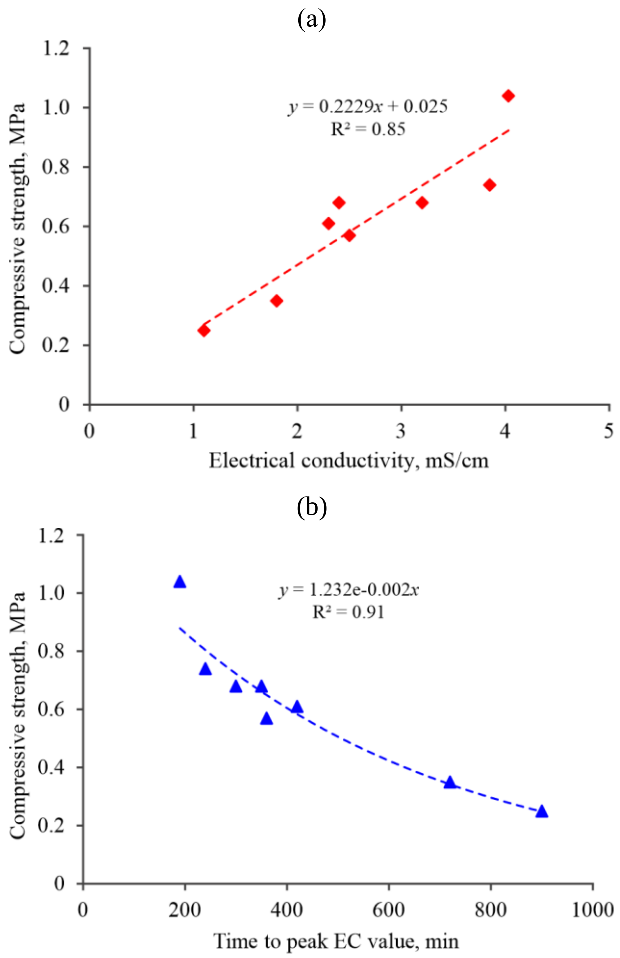

Figure 22. Correlation of early paste backfill mass strength with electrical conductivity parameters (3 days): (a) peak value; (b) time for reaching a peak value

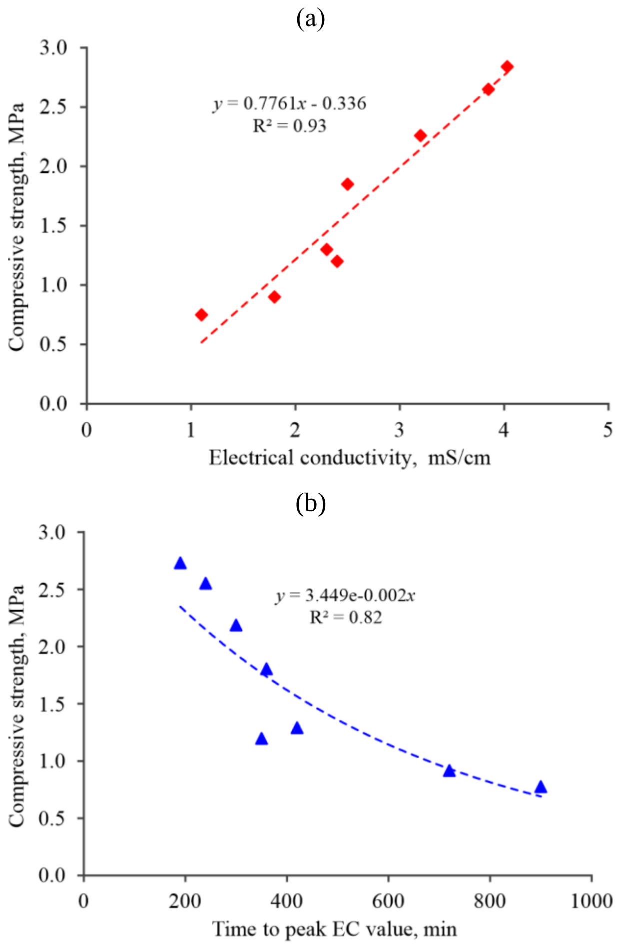

Figure 23. Correlation of late paste backfill mass strength with electrical conductivity parameters (56 days): (a) peak value; (b) time for reaching a peak value

Figures 22a, b analysis shows that at the early stage of hardening, the paste backfill mixture strength demonstrates a linear dependence on the peak value of electrical conductivity with a high correlation coefficient. Strength decreases exponentially with increasing time to peak, which confirms the importance of the intensity of the initial hydration processes.

Figures 23a, b shows that at the later stage (56 days), the linear dependence between electrical conductivity and strength is enhanced, which is manifested in a greater sensitivity of strength to changes in electrical conductivity. The exponential dependence of strength on the time to reach the peak electrical conductivity value is also preserved, indicating a significant influence of the time to peak on the kinetics of the formation of a strong mixture structure. For early strength (3 days), the correlation coefficient indicates a strong relationship, but it is somewhat weaker than at the late stage (56 days).

Using the superposition principle, the regression models are combined to obtain a general predictive strength model that takes into account the influence of electrical conductivity and time to peak of electrical conductivity through linear and exponential dependences, where each parameter contributes independently to the final strength value:

$$R(t) = \alpha \cdot EC + \beta \cdot e^{-\gamma \cdot \tau}, \quad (2)$$

where:

$R(t)$ – the predicted strength in t days;

EC – the peak electrical conductivity value of the mixture, mS/cm;

τ – time to peak of electrical conductivity, hours;

α, β, γ – coefficients depending on the ageing (term) of the mixture.

For early ageing (3 days):

$$R_3 = 0.222 \cdot EC + 1.232 \cdot e^{-0.002 \cdot \tau}. \quad (3)$$

For a later ageing (56 days):

$$R_{56} = 0.776 \cdot EC + 3.449 \cdot e^{-0.0012 \cdot \tau}. \quad (4)$$

The resulting model is valid for a binder material dosage of 6% of the solid part content and a total solid part content of 75% in the paste backfill mixture and allows in some cases to refuse expensive cube tests using electrical conductivity measurements of small mixture portions, which saves time and resources.

4. Examples of implementation of the concept of using paste backfilling technology to restore the earth's surface

A preliminary analysis of the state of earth's surface, disturbed by complex iron ore mining in the city of Kryvyi Rih, which occupies the main part of the Kryvyi Rih Iron-ore Basin, has been conducted [42]. It has been found that with a city area of 49 thousand hectares, 21 thousand hectares or 49% of the land has been disturbed. Moreover, 65.25% of the total disturbed land area are accumulated industrial waste – quarry and mine rock dumps, tailings dumps for iron ore beneficiation, metallurgical slag dumps, while 34.76% is disturbed by quarrying, as well as shear zones and mine failure zones. Thus, it becomes obvious that there is a critical technogenic and ecological situation in the region.

Among the hazardous forms of the earth's surface disturbance, it is necessary to distinguish the failure zones of active and closed mines, as well as unfilled cavities of old closed and shallow mines. These forms of disturbance are sudden, unpredictable and threaten public safety, infrastructure, valuable soil and ecosystems. Particular attention should be paid to identifying unfilled cavities in old closed shallow mines. The difficulty is that there is no reliable information on their location, as the mines are very old and mining plans have been lost over time. To solve this important task, it is necessary to develop a comprehensive toolkit consisting of geophysical research methods and the use of modern GIS programs.

Today, the depth of iron ore mines in the city of Kryvyi Rih is 1300-1500 m, and the impact of the stoping on the earth's surface has been significantly reduced, as the critical mining depth has been reached, as a result of which the active phase of shear processes has stopped. In this case, unexpected, abrupt earth's surface failures are practically impossible [64], but residual deformation processes with the spread of shift trough occur, which can influence the unfilled cavities of old shallow mines, creating failure zones.

Given that the critical mining depth has already been crossed, it is believed that the transition from mining systems with rock caving and stope mining systems to mining systems with backfilling of underground cavities is ineffective, as it will no longer solve the existing complex geomechanical situation and will lead to significant economic costs for backfilling operations. However, it is possible to improve the geomechanical situation by backfilling the formed technogenic cavities directly from the earth's surface, which is a new direction.

A conceptual scheme for the development of backfilling operations in the western part of the city of Kryvyi Rih has been drawn up (Fig. 24). The scheme shows the following elements: active quarries; flooded quarries; quarries at the stage of filling; closed and insufficiently reclaimed quarries, where there are cavities and no further use of them; tailings dumps as the main component for cemented paste backfilling, sources of binder materials, positions for placing a mobile backfilling complex, and an approximate backfill pipeline network.

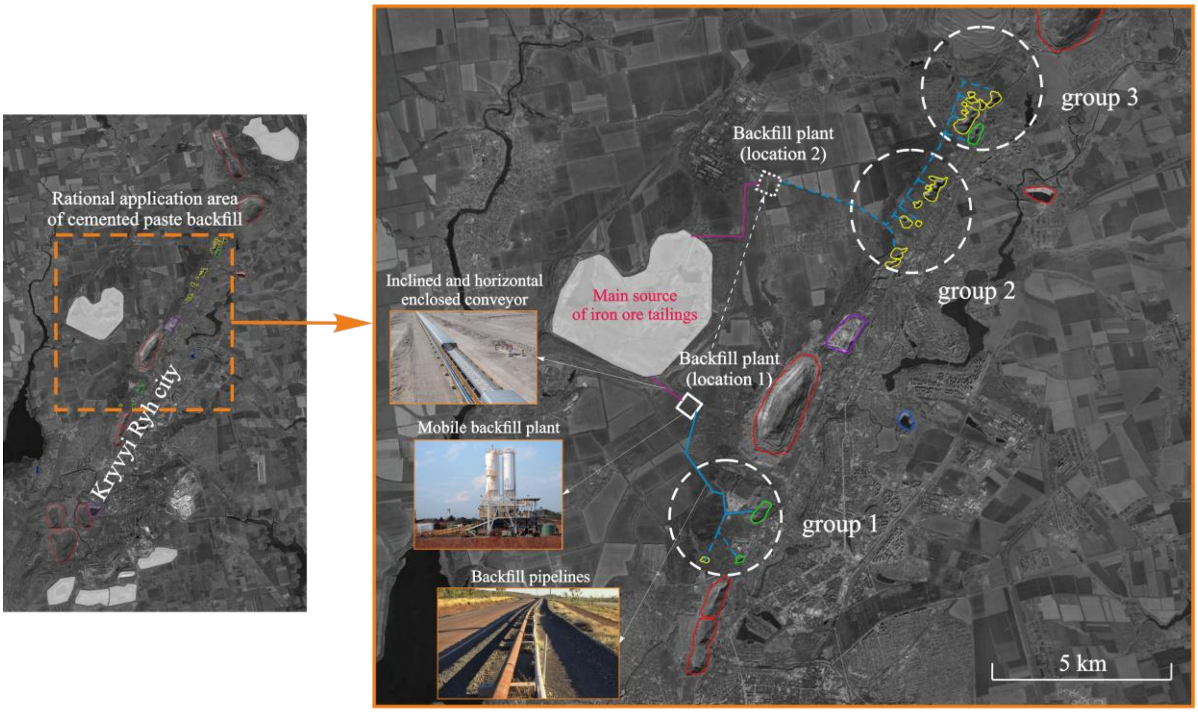

Figure 24. The concept of paste backfilling of surface technogenic cavities in the western part of the city of Kryvyi Rih: ■ ***tailings dumps;*** **—** ***inactive quarries ready to be backfilled;*** **—** ***failure zones ready to be backfilled;*** **—** ***active quarries;*** **—** ***flooded quarries;*** **—** ***quarries at the stage of filling with rocks;*** **—** ***conveyor line;*** **—** ***backfill pipeline route;*** **▪ ▪ ▪** ***further route of the backfill pipelines***

To improve the earth's surface state, minimize the development of deformation processes and restore land areas, a comprehensive concept of cemented paste backfilling techno-logy for technogenic cavities formed as a result of underground and open-pit mining operations is proposed. The concept is reasonable to implement in the western part of the city of Kryvyi Rih, which is affected by numerous failure zones, quarry cavities and accumulations of industrial waste. To implement the proposed concept, a number of favorable technological, economic and environmental conditions have been identified:

– the disturbed land areas are located within a large industrial center with a high population density;

– the presence of available technogenic cavities for backfilling;

– the presence of a tailings dump as a source of finely dispersed beneficiation tailings;

– existence of an alternative mineral and raw material base for backfill materials;

– dusty dry beaches of tailings dumps and environmental pollution;

– difficulty in allocating new land areas for waste disposal;

– imperfection of backfilling technogenic cavities with dump waste rock;

– relatively insignificant distance of the tailings dump to the formed technogenic cavities;

– the earth's surface disturbance is the responsibility of several entities;

– a favorable relief and topographic situation for laying pipelines.

The most important peculiarity of the proposed concept is the location of a large tailings dump (reserves of 700 million tons) and its close proximity to the resulting technogenic cavities. To implement the concept of paste backfilling, it is reasonable to systematize technogenic cavities into 3 groups (1, 2, 3). Priority are groups 1 and 2, as the paste backfill mass transportation distance is estimated in the range of 4-5.5 km. Generalized data on groups of technogenic cavities, their types, cavity volumes, transportation distances and recommended methods for backfilling are given in Table 6.

Figure 24 shows the proposed paste backfilling technology, which involves the selection of beneficiation tailings from the dry beaches of the tailings dump of PJSC Central Iron Ore Enrichment Works. The tailings are loaded at a point with a receiving hopper and transported by inclined and horizontal closed conveyors to a mobile backfill complex. The tailings are mixed with water and binder materials. The granulated slag is delivered in a fraction of 0-5 mm and crushed in a ball mill. The finished paste mixture is supplied by pressure pumps through surface pipeline systems to mine failure zones, identified unfilled underground cavities and mined-out quarry spaces. After backfilling the technogenic cavities of group 1, the mobile backfill complex is dismantled from position 1 to position 2 to perform backfilling operations in technogenic cavities of groups 2 and 3. Based on the research performed above, it is recommended to consider the recommended composition of the paste backfill mixture (100%) as a basis: 4.5% of binder material, 70.5% of finely dispersed iron ore beneficiation tailings, 25% of water, and binder material is combined (30% of cement and 70% of blast-furnace granulated slag).

Table 6. Grouping of technogenic cavities and recommendations for methods of backfilling

Group designation	Type of technogenic cavities	Volume of created cavities, mln. m^3	Transportation distance, km	Recommended method of backfilling
Group 1	2 closed quarries, 1 failure zone, unknown shallow mine cavities	14.5	4.0-4.5	*Failure zones:* cemented paste backfilling with possible addition of crushed waste rock fractions (before failures) and special additives. *Underground cavities of shallow closed mines:* drilling of wells for backfilling from the earth's surface with the supply of cemented paste backfill mass. *Mined-out spaces of closed quarries:* combined method of backfilling using cemented paste backfilling (April – October) and rock bulk backfilling (November – March).
Group 2	6 failure zones, unknown shallow mine cavities	15.3	5.0-5.5	
Group 3	1 closed quarry, 7 failure zones, unknown shallow mine cavities	21.0	8.5-10.3	

The proposed concept of paste backfilling in the region is quite flexible and mobile in use. Thus, it is reasonable to fill the mined-out space of a quarry or a failure zone of the earth's surface with paste backfilling in the warm season (April-October), while in the cold season and unfavorable climatic conditions, the surface pipeline system is reoriented to backfill the identified underground cavities of old unclosed mines. This approach creates uninterrupted performance of backfilling operations and eliminates equipment downtime.

The mobile backfill complex should consist of the following elements: roll crusher for crushing tailings, receiving hopper with a metering feeder, warehouses for granulated slag and cement, slag crushing mill, silos for storing binder materials, batchmeters for supplying the mixture components, spiral-blade mixer for uniform mixing, and a piston pressure pump for pumping the finished paste mixture through a system of surface-laid pipelines.

A set of environmental, economic and social positive changes in the region has been formed in the implementation of the proposed technology for restoring the earth's surface, which is as follows: reducing dust pollution of the environment; utilization of harmful finely dispersed tailings, dump waste rock and metallurgical slag; restoration and return of land areas; possibility of reusing alluviation maps of tailings dumps; minimizing landslide processes on the earth's surface, which increases the safety of health and life of the population, allows preserving infrastructure facilities and reducing the degradation of valuable soils and ecosystem biodiversity; improving the psychological state of the population; enhancing the environmental image of mining enterprises and government bodies. It has been determined that using the proposed technology for backfilling all surface technogenic cavities in the western outskirts of the city of Kryvyi Rih, ready for backfilling, it is possible to restore up to 200 hectares of the earth's surface, utilize 25 million tons of finely dispersed beneficiation tailings, 13 million tons of dump waste rock and 3.5 million tons of metallurgical slag.

To achieve an effective cost-sharing balance, an industrial-economic symbiosis can be formed between mining enterprises that have caused damage to the earth's surface, and state, regional or local authority bodies that should be interested in improving the environmental situation, health and well-being of the population, as well as should strive for rational land use and economic development of the region and city. The implementation of such projects, given their scale and importance, will probably require amendments to current legislation aimed at simplifying approval procedures, regulating the use of restored lands, and introducing incentive mechanisms to attract investors.

The directions for further research should be the study of the transformation of the geomechanical situation of the rock mass when it is filled using paste backfilling and the substantiation of technological parameters for preparation, transportation and formation of the backfill mass in technogenic cavities.

5. Conclusions

1. The performed analysis has shown that today there are attempts to reorient the technologies of monolithic backfilling, including cemented paste backfilling, from underground to open technogenic cavities. However, the properties of cemented paste backfill mass, namely in the conditions of hardening in the open environment, need to be studied. In addition, the situation with the development of the concept of backfilling in conditions of complex earth's surface disturbance – mine failure zones, unfilled cavities of old closed mines and mined-out spaces of closed dry quarries – is insufficiently studied.

2. It has been revealed that a paste-like homogeneous state of the backfill mixture based on iron ore beneficiation tailings from Ukrainian mining and processing plants is achieved at a solid part content (tailings) of about 73-75%, which provides an optimal balance between its flowability and mechanical strength.

3. A method for predicting the early and late strength of paste backfill mass has been developed, based on the identified patterns between the electrical conductivity of the paste mixture, the time to reach its peak, and the strength at different stages of hardening. A general regression model based on the principle of superposition of the influence of factors has been obtained, where the linear contribution of electrical conductivity and the exponential contribution of time to the peak reflect their independent influence on strength gain. The method allows for strength estimation without sample preparation with an accuracy of 85-90% using rapid measurements of small portions of the mixture, making it a cost-effective and practical tool for quality control and optimization of paste backfill mass composition.

4. A set of patterns has been determined for paste backfill mixture based on pure cement as a reference and main traditional binder material. It has been found that an increase in the cement content in the mixture increases electrical conductivity and accelerates hydration processes, which reflects more intensive material structure formation. Compressive strength shows a linear increase with the increase in the cement share and also depends on the solid part content of the mixture: higher concentration of solid particles contributes to accelerated strength gain. The influence of hardening time is manifested in the gradual formation and stabilization of

strength characteristics, which emphasizes the role of cement in ensuring the reliability and durability of paste backfilling.

5. The strength characteristics of paste backfill mixture at different variations of the binder material have been tested. It has been revealed that when using 6% binder material and 75% solid part in paste backfill mixtures, replacing cement with slag up to 70% gradually reduces the strength. The best balance is achieved at cement/slag ratio of 70/30, providing high strength. The 30/70 composition also demonstrates acceptable strength (1.5-2.5 MPa for 28-56 days), sufficient for filling cavities and reclamation, making it economically viable due to reduced cement costs and the use of metallurgical waste. The addition of limestone or dry ash does not provide a significant improvement, since these components are less active in hydration processes.

6. The knowledge and understanding of the physical-mechanical properties of cemented paste backfill mass made of natural and technogenic materials of the Kryvyi Rih Region have been further developed at a binder material content of 6% of the solid part in the mixture and a total solid part content of 75% in the conditions of hardening under the influence of climatic environmental conditions.

7. A concept has been developed for using cemented paste backfilling to eliminate formed surface technogenic cavities caused by the influence of underground and open-pit mining operations. The concept provides flexibility in performing operations, allowing for the backfilling of various types of technogenic cavities and includes uninterrupted operation during the warm season with a paste mixture in failure zones or quarry cavities, and reorientation to backfilling underground cavities in winter. This approach helps to restore land, utilize beneficiation waste, reduce dust pollution, minimize shear processes, and also creates a basis for the rational use of restored territories, contributing to the environmental, economic and social development of the region.

Author contributions

Conceptualization: MP; Data curation: MP, KS; Formal analysis: MP, KS; Funding acquisition: MP; Investigation: MP, KS; Methodology: MP, KS; Project administration: MP; Resources: MP, KS; Software: MP, KS; Supervision: MP; Validation: KS; Visualization: MP; Writing – original draft: MP, KS; Writing – review & editing: MP, KS. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

Authors MP and KS declared that they were editorial board members of the Mining of Mineral Deposit journal at the time of submission. This had no impact on the peer review process and the final decision.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Дослідження властивостей цементованого пастового закладання та варіанти його застосування: на прикладі Криворізького залізорудного басейну, Україна

М. Петльований, К. Сай

Мета. Експериментальні дослідження комплексу властивостей цементованого пастового закладання на основі низки природно-техногенних матеріалів Криворізького залізорудного басейну з метою його подальшого використання у технологіях відновлення сильно порушеної земної поверхні комплексним видобутком залізних руд.

Методика. Застосовано комплексний інструментарій: рентгенофлюоресцентний та рентгенодифракційний аналізи дослідження хімічного і мінералогічного складу компонентів, вимірювання кондуктометром електропровідності сумішей при їх твердінні, лабораторні дослідження приготування пастових закладних сумішей та визначення їх фізико-механічних характеристик на лабораторному гідравлічному пресі, аналітичне дослідження для визначення сприятливих регіонів для пастового закладання з урахуванням наявності техногенних пустот, хвостосховищ та в'яжучих матеріалів.

Результати. Виявлено, що пастоподібний однорідний стан закладної суміші з використанням хвостів збагачення залізних руд гірничо-збагачувальних комбінатів України досягається при вмісті твердої частини близько 73-75%, що забезпечує оптимальний баланс між її текучістю та механічною міцністю. Встановлено комплекс закономірностей зміни міцності від дозування в'яжучого, вмісту твердої частини та терміну твердіння для пастового закладання на основі чистого цементу та при різних варіаціях альтернативних в'яжучих матеріалів. Встановлено закономірності зв'язку міцності пастового закладання з параметрами електропровідності суміші.

Наукова новизна. Розроблено метод прогнозування ранньої та пізньої міцності пастового закладання, який базується на встановлених закономірностях між електропровідністю пастової суміші, часом до досягнення її піку та міцністю на різних стадіях твердіння. Отримало подальший розвиток знання і уявлення щодо фізико-механічних властивостей цементованого пастового закладання в умовах твердіння під впливом кліматичних умов навколишнього середовища.

Практична значимість. Проведені дослідження властивостей пастового закладання є корисними для проєктування технології відновлення сильно порушеної земної поверхні, а саме закладанні провальних зон земної поверхні від впливу залізорудних шахт, закладання виявлених підземних непогашених пустот закритих шахт та вироблених просторів закритих кар'єрів. Розроблена концепція реалізації пастового закладання у західній частині м. Кривий Ріг, що сприятиме екологічному, економічному та соціальному розвитку регіону.

Ключові слова: *цементоване пастове закладання, хвости збагачення, в'яжучий матеріал, міцність, електропровідність, провальні зони, кар'єрні пустоти*

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