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SUBSTANTIATION OF RATIONAL BACKFILL COMPLEX PLACEMENT WHEN ELIMINATING TECHNOGENIC CAVITIES OF IRON-ORE DEPOSITS BASED ON PASTE BACKFILLING TECHNOLOGY

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Abstract. The research purpose is to substantiate the rational placement of the backfill complex to ensure the effective elimination of technogenic cavities formed as a result of underground and open-pit mining of iron-ore deposits, taking into account the rheological properties of paste backfill mixtures and minimizing transportation costs. The research uses an experimental method, including the preparation of paste mixtures with a solid part content of 73–75% and the study of their rheological characteristics using the NDJ-8AT digital rotational viscometer. The method of technical-economic modeling is also used to estimate the capital and operating costs of transporting the paste mixture through a pipeline and conveyor depending on the variable distance between the tailings dump and the backfill complex, as well as to determine its optimal placement by minimizing the total costs. The expediency of using the Herschel-Bulkley model to describe the rheological behavior of paste backfill mixtures based on beneficiation tailings, which form the basis for determining a set of parameters for their transportation through pipeline transport, has been proven. It has been found that the total transportation costs are parabolic in nature and reach a minimum at the balance of pipeline and conveyor lengths, which makes it possible to determine the optimal zone for the placement of the mobile backfill complex, which is located within 3300–4700 m from the tailings dump. Rational locations and positions for moving the mobile backfill complex between groups of technogenic cavities are recommended. The Herschel-Bulkley rheological models for paste backfill mixtures with a solid part content of 73–75%, made from coarse iron-ore beneficiation tailings, have been specified. For the first time, a comprehensive model for optimizing the placement of a mobile backfill complex is proposed, taking into account the rheological properties of the mixture and combined transportation. The results are useful in applying the concept of eliminating technogenic cavities in iron-ore regions, namely, in planning the placement of a mobile backfill complex for eliminating technogenic cavities, in particular in the Kryvyi Rih Basin. The implementation of the concept may improve the environment through the utilization of beneficiation tailings, to block the development of the earth's surface deformations and to fully restore the disturbed land areas.

Keywords: technogenic cavities, iron-ore deposits, concept, beneficiation tailings, paste backfilling, optimization, minimization, costs.

1. Introduction

Today, mining of minerals plays an important role not only in ensuring the technological progress of humanity, but also in the sustainable development of many countries with resource-based models of economies [1–3]. The economies of countries with a strong raw material base are heavily dependent on mining industry, which provides receipts of foreign exchange earnings, filling the budget and creating jobs. However, the intensive mining of mineral deposits is accompanied by a significant anthropogenic impact on the environment [4–6], which is manifested in the earth's surface disturbance, natural landscape degradation, air/soil/water pollution, large-scale accumulation of industrial waste, as well as in the formation of technogenic cavities in the subsoil.

Environmental and technogenic problems are particularly acute in mining regions where open-pit and underground mining methods are simultaneously used. In Ukraine, such a region is the Kryvyi Rih Iron-ore Basin, where over 100 years of open-pit and underground mining of low-grade and high-grade iron-ore deposits has led to a severe technogenic and environmental situation. The most urgent problem is the disturbance of the earth's surface continuity (mine failure zones, sudden caving, closed quarries), since mining of minerals in the Kryvyi Rih Basin is carried out in

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close proximity to industrial and residential facilities of the city of Kryvyi Rih. Today, mining operations around the city of Kryvyi Rih have disturbed more than 21 thousand hectares of the earth's surface area, and the volume of accumulated mining and metallurgical waste has reached 11 billion tons [7–9]. For the purpose of land reclamation, filling of failure zones and closed quarries with waste rock is currently used, but this is done only locally and provided that there is a source of dump waste rock near the cavities. However, the formed loose mass, especially in failure zones, does not guarantee blocking the further development of dangerous deformation processes [10, 11]. In this regard, there is a need to develop more efficient and scientifically sound approaches to restoring the geomechanical stability of the earth's surface in the context of active mining of iron-ore reserves for the conditions of the Kryvyi Rih Basin.

To solve this scientific problem, the transition from the formation of a loose rock mass to the creation of a monolithic backfill structure within technogenic cavities has been identified as a priority. For this purpose, based on the study of the topographic situation of intensive mining areas around the city of Kryvyi Rih, the diversity of the mineral and raw material base of potential backfill materials, the advantages/disadvantages of types of backfilling, the expediency of using the paste backfilling technology has been scientifically substantiated [12]. For the first time, the concept of complex elimination of technogenic cavities using paste backfilling technology [7, 13] is proposed, which today remains insufficiently studied in the scientific environment. A comprehensive geospatial analysis of the compatibility of tailings dumps and the group of technogenic cavities formed has identified the most appropriate area for applying the proposed concept. Such an area is the western outskirts of the city of Kryvyi Rih, where a large tailings dump of PJSC Central Iron Ore Enrichment Works has been formed, which should be considered as the main component of paste backfilling. At the same time, there are a number of technogenic cavities (failure zones, unfilled underground cavities, closed quarries) in moderate proximity to it, which are systematized into 3 groups.

The concept involves the selection of beneficiation tailings from alluviation maps, from which the drainage has already occurred, their transportation by an inclined and horizontal closed-type conveyor line to the mobile backfill complex, preparation of the paste backfill mixture, its further transportation from the complex to technogenic cavities by pressure method through the laid ground-based system of backfill pipelines, as well as direct formation of a monolithic backfill mass.

The implementation of such a long-term concept requires an optimal balancing of costs, as the location of the mobile backfill complex largely determines the total transportation costs. In order to achieve economic efficiency and minimize total costs, it is important to ensure a rational ratio between the length of the conveyor line for supplying dewatered tailings from the tailings dumps and the length of the backfill pipelines through which the paste mixture is fed to the technogenic cavities.

Thus, the presented research aims to determine the rational backfill complex location between the tailings dump, as the main source of inert aggregate for paste backfill mixtures, and the formed groups of technogenic cavities as a result of underground and open-pit mining operations in the conditions of the Kryvyi Rih Iron-ore Basin.

2. Research methods

In the implementation of the concept of eliminating technogenic cavities based on paste backfilling, the transport chain is represented by two elements: conveyor transport to feeding beneficiation tailings directly from the tailings dump to the mobile backfill complex, as well as pipeline transport for moving of the produced paste backfill mixture from the backfill complex to the specified technogenic cavities.

The most challenging part is the process of transporting the paste backfill mixture, since pipeline transport requires ensuring a continuous pressure regime, overcoming significant hydraulic resistance in pipelines and taking into account the rheological properties of paste mixtures. While for conveyor transport, costs are determined based on the transportation volumes and the choice of a conveyor with the appropriate capacity, then for pipeline transport, it is necessary to additionally take into account the pipeline diameter, energy consumption for pumping, and the maximum transportation distance, which necessitates the mandatory determination of the rheological characteristics of the paste mixture, in particular the ultimate shear stress and viscosity.

The most important thing is to study the paste mixture shear stress at a variable shear rate [14, 15]. The need to determine these parameters is because paste backfill mixtures are non-Newtonian fluids, that is, their viscosity is not constant and varies depending on the applied mechanical influence, in particular, the shear rate. To study such materials, it is advisable to use specialized devices – rotational viscometers, which make it possible to fix the change in the rotational resistance of a spindle immersed in the mixture, and on this basis to calculate the appropriate rheological parameters. Previous studies have shown that the paste state of the backfill mixture based on iron-ore beneficiation tailings is achieved at a total solid part content of 73–75% (tailings + cementitious material). The content of cementitious material (Portland cement) in the mixtures is 6% of the total solid part or 4.5% by weight of all components of the mixture. Beneficiation tailings from mining and beneficiation plants are selected from maps of their tailings dumps and are characterized by their granulometric composition as coarse (–20 μm < 35%). The experimental compositions of the paste backfill mixtures are shown in Table 1. Further transportation parameters are determined based on the most viscous mixture (complex conditions) with 75% of solid part content.

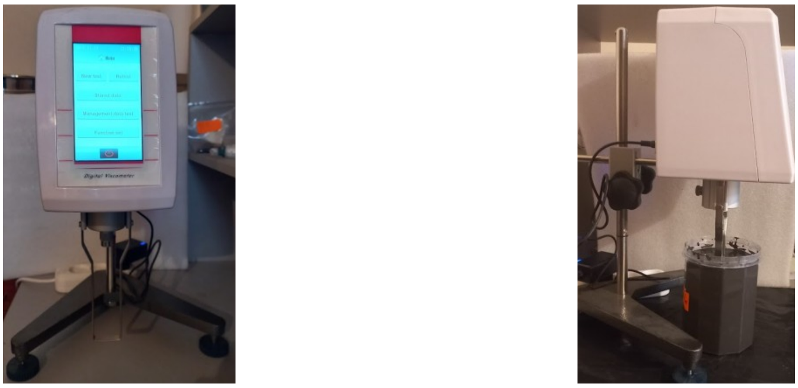
This research uses NDJ-8AT digital rotational viscometer to determine the dynamic and kinematic viscosity of thick suspensions in the range of 0–2000 Pa·s, including backfill pastes based on fine-grained aggregate. The device view is shown in Figure 1. The viscometer allows measurements to be made at 6 fixed rotational velocities: 0.3, 3, 6, 12, 30 and 60 rpm, which corresponds to shear rates in the range of 0.62 to 12.48 s^{-1}.

This range is sufficient for studying the behavior of the mixture under low shear load conditions, but in real conditions of transporting the paste mixture through pipelines, depending on the flow rate and internal diameter of the pipes, much higher shear rates are formed – up to 100 s^{-1} and more. Therefore, to take into account this difference and to predict the actual paste mixture behavior during transportation, the results of viscosity measurements in the range of 0.62...12.48 s^{-1} are extrapolated to higher shear rates using an appropriate rheological model of the paste mixture behavior. Paste backfill mixtures, sufficient for a volume of measuring container (550 cm^3), were produced for conducting experiments at a mixture density of 1.9–2.0 t/m^3.

Table 1 – Formulations of experimental paste backfill mixtures

Mixture index	Cement, %	Beneficiation tailings, %	Water, %	Total solid part content, %
P-(CT)-6-75	4.5	70.5	25	75
P-(CT)-6-74	4.5	69.5	26	74
P-(CT)-6-73	4.5	68.5	27	73

Note: P – paste mixture; C – Portland cement; T – iron-ore beneficiation tailings



(a) (b)

Figure 1 – NDJ-8AT digital rotational viscometer: general view of the rotational viscometer (a); testing of the paste backfill mixture (b)

The experimental program included the construction of a rheological curve of the "shear stress – shear rate" dependence. The data obtained are used to approximate a mathematical model that most effectively and accurately describes the studied paste system. Depending on the nature of the dependence curve, the appropriate rheological model is selected, such as the Bingham, Herschel-Bulkley, Oswald-de-Ville, etc. [16–18].

The method of technical-economic optimization based on variable cost modeling was used to substantiate the rational placement of the backfill complex between the tailings dump and a group of technogenic cavities (mine failure zones, unfilled underground cavities, closed quarries) [19, 20].

The essence of the model for optimizing the total reduced costs for transporting the backfill mixture is as follows. The maximum total length of transportation in the model is assumed to be L_{tot} = 12000 m, covering the maximum distance from the tailings dump to the most distant group of cavities 3. The length of the closed horizontal conveyor line X for transporting beneficiation tailings (inert aggregate) from 0 to 12000 m is taken as a variable, and the length of the pipeline transport of the paste mixture will vary accordingly by the expression $L_{mp} = L_{total} - X$.

Since the inclined section of the conveyor from the tailings dump working map to the lower point of the transfer to the horizontal part of the closed-type conveyor is structurally necessary, fixed in length and does not change when the location of the mobile backfill complex is varied, its capital costs are not taken into account in the optimization model. The calculations take into account only the variable part of the horizontal conveyor line – from the lower base of the tailings dump to the point of the backfill complex placement. Given these peculiarities, the calculation scheme of the problem is illustrated in Figure 2.

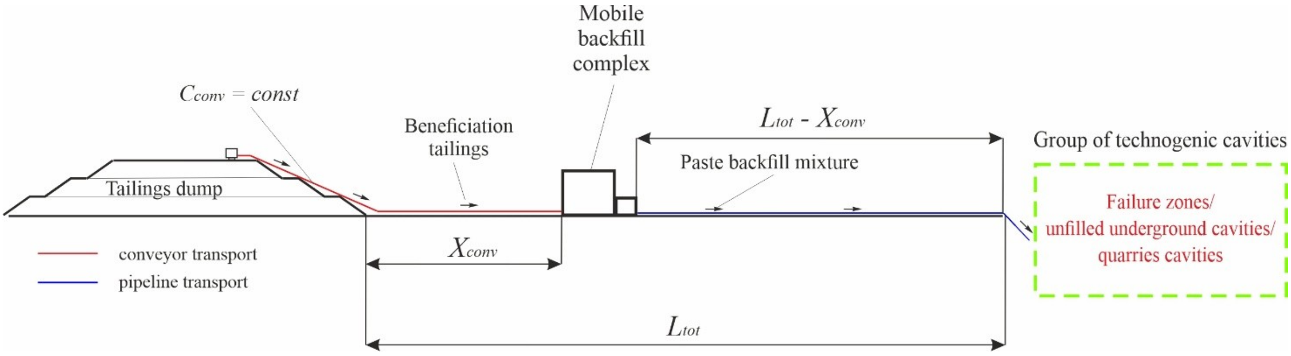


Figure 2 – Calculation scheme for determining the optimal location of a mobile backfill complex

When using the optimization method, the following was taken into account: capital costs per 1 m of each type of transport, operating costs for electricity (UAH/m), a gradual increase in the power consumption of the conveyor with an increase in its length, as well as additional costs associated with exceeding the permissible length of the mixture transportation (over 7000 m), which necessitates the installation of a second piston pump and is accompanied by an almost double increase in energy consumption, complicated operation and increased technical risks.

The total cost optimization model is as follows:

$$Z(X)=Z_{conv}(X)+Z_{pip}(X)\rightarrow \min \quad \text{UAH}, \qquad (1)$$

at $X \in [0;\ 12000\,m]$,

where Z_{conv} – is the total costs of transporting the paste using conveyor transport over a distance X from the tailings dump to the backfill complex, UAH; Z_{pip} – total cost of transporting the paste mixture through pipeline over a distance $L_{total} - X$ from backfill complex to technogenic cavities, UAH.

3. Results and discussion

3.1. Structural elements of transportation processes in the new concept of eliminating technogenic cavities

The rational area for concept implementation of eliminating technogenic cavities based on paste backfilling is located on the western outskirts of the city of Kryvyi Rih, where the main source of inert aggregate is located, namely the tailings dump of

PJSC Central Iron Ore Enrichment Works and groups of technogenic cavities 1, 2 and 3 in moderate proximity to it. Using the Google Earth software, it has been determined that the direct distance from the tailings dump to the cavities is: 5–6 km to cavity group 1, 6.5–7.5 km to cavity group 2, and 9.5–10.5 km to cavity group 3, which should be further specified taking into account the actual relief and situational plan of the area. Therefore, based on Figure 2, it is advisable to first perform backfilling operations in technogenic cavities of group 1, and only then in groups 2 and 3. In this case, it is more technologically and economically feasible to consider the scheme of transporting the paste mixture to technogenic cavities with the movement of a mobile backfill complex, while the backfill complex placement position 1 should be connected separately with group of cavities 1, and placement position 2 – with groups 2 and 3. The mutual arrangement of the tailings dump, the groups of technogenic cavities and the necessary structural transportation elements is illustrated in Figure 3.

Each transport line from the tailings dump to the group 1, 2 and 3 technogenic cavities should include a certain length of closed-type horizontal conveyor line, a defined location of the mobile backfill complex and a certain length of backfill pipeline route. After completing the feeding of the paste mixture to cavity group 1, the mobile backfill complex is dismantled, moved to the next group (group 2 or 3) and reused without the need to build a new facility, while inclined and horizontal conveyor lines can be reused in the new transport chain with an increase in their length if necessary.

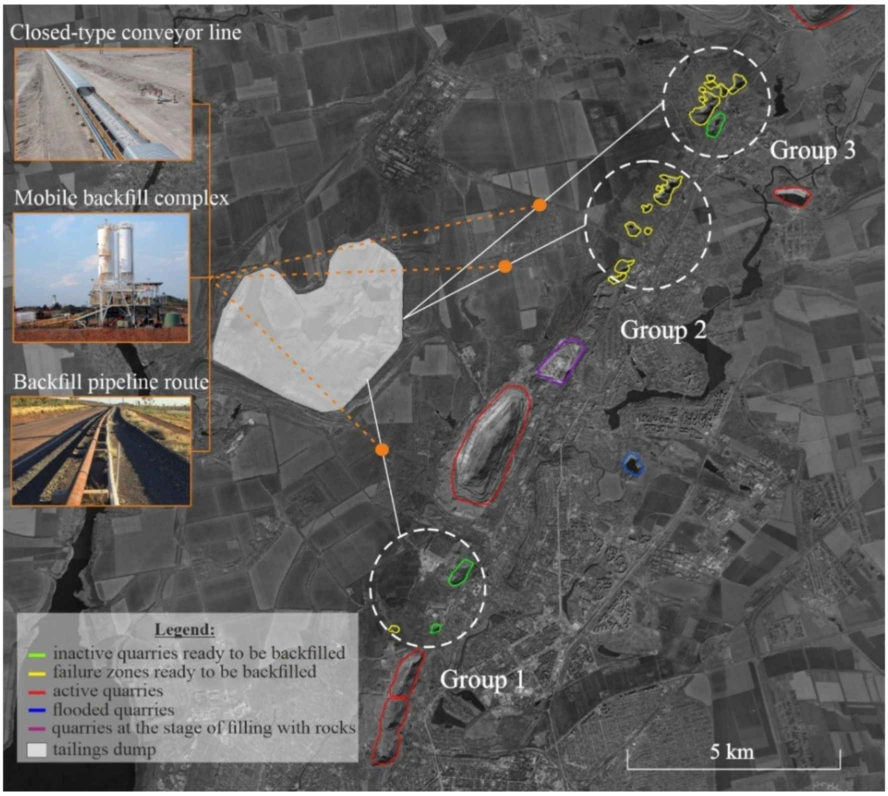


Figure 3 – Elements of transportation processes in the new concept of eliminating technogenic cavities in Kryvyi Rih Basin

The proposed scheme, as opposed to the option with a stationary permanent placement of the complex, significantly reduces the total length of pipelines at each stage of backfilling the cavity groups, minimizes hydraulic friction losses, eliminates the need for additional pumping stations and reduces overall operating costs. The shorter pipeline length also reduces the risk of unstable mixture flow, blockages and the need for frequent flushing. To implement such a scheme, an important scientific-technical task is to determine the optimal location of the backfill complex from the tailings dump, which minimizes total costs and ensures the transportation of the paste mixture by one pumping station without the need for booster pumps.

3.2. Study of rheological properties of paste backfill mixtures

In the course of experimental tests of rheological properties using a digital viscometer, it has been found that at low rotational velocities, in our case 3 rpm, corresponding to a shear rate of approximately 0.62 s^{-1}, the device did not fix the shear stress. In this case, the registration began with 6 rpm (1.24 s^{-1}), indicating the presence of a threshold (limit) shear stress in the paste mixture. This characteristic is the first sign of the rheological behavior of a paste mixture according to the Herschel-Bulkley model, where no flow occurs until a certain critical load is reached. Given the impossibility of direct measurement in the range below 1.24 s^{-1}, to confirm the paste behavior model, analytical approximation of experimental points and extrapolation of curves to the intersection with the axis of Y were used further, thereby determining the conditional shear stress threshold corresponding to the beginning of the flow. As a result of the research, the dependence of shear stress of the studied paste mixtures on the shear rate has been revealed.

Analysis of dependences (Fig. 4) between shear stress τ and shear rate γ for paste mixtures with different solid phase content (73, 74 and 75%) shows a clearly expressed non-linear increasing dependence, indicating that as the shear rate increases, the resistance of the mixture to deformation increases, but disproportionately with a tendency to reduce viscosity, which is a characteristic sign of pseudoplastic behavior.

Such rheological properties are typical of non-Newtonian fluids, where viscosity is not a constant value, but depends on the applied mechanical load, that is, the shear rate. In this case, curves indicate the presence of a threshold (limit) shear stress below which flow does not occur, which excludes the possibility of describing the behavior of the mixture according to the Newton model, which assumes a linear dependence, or according to the Bingham model, which adds a threshold value, but assumes a linear dependence after it is reached.

Also, the shape of the curves and the corresponding exponent values of $n < 1$ confirm the pseudoplastic character, namely, the higher the shear rate, the lower the increase in shear stress becomes, while the values of the approximation coefficients $R^2 = 0.92…0.95$ indicate a high level of compliance with experimental data. Thus, based on the nature of the dependences, it can be stated that paste mixtures are described by the Herschel-Bulkley rheological model, which has the form:

$$\tau = \tau_0 + K \cdot \gamma^n, \tag{2}$$

where τ_0 – yield strength, Pa; K – consistency index, Pa·s^n, n – flow index, a dimensionless value indicating the degree of pseudoplasticity; γ – shear rate, s^{-1}.

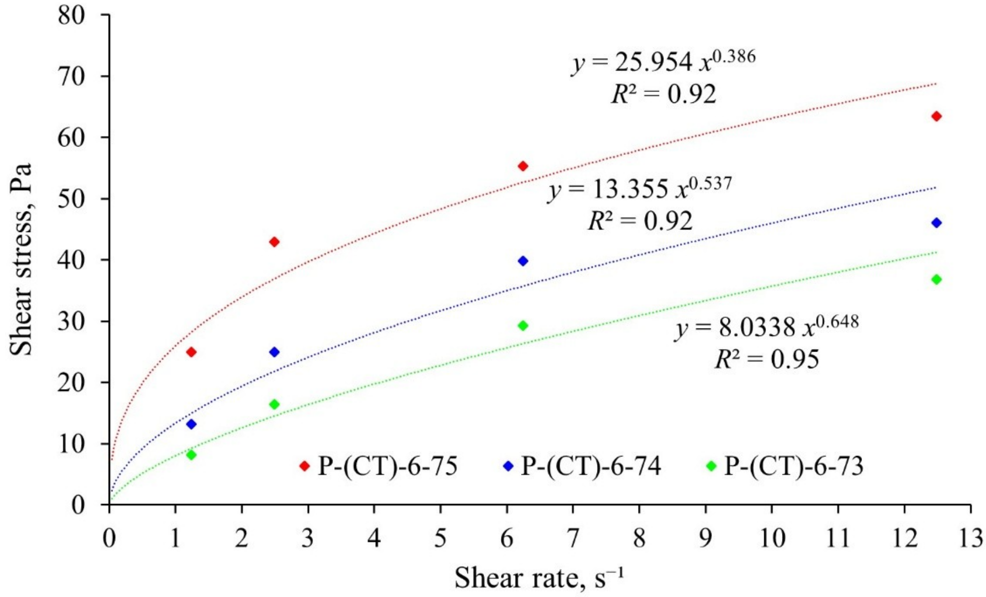


Figure 4 – Dependence of the shear stress of a paste mixture on the shear rate at different values of the total solid part content (73, 74 and 75%)

The experimental data obtained were approximated with consideration of Y-axis elongation (to determine τ_0) according to the Herschel-Bulkley rheological model by the dependences of the type:

– mixture P-(CT)-6-75:

$$\tau = 8 + 25.954 \cdot \gamma^{0.386} \text{ Pa;} \tag{3}$$

– mixture P-(CT)-6-74:

$$\tau = 4 + 13.355 \cdot \gamma^{0.537} \text{ Pa;} \tag{4}$$

– mixture P-(CT)-6-73:

$$\tau = 2 + 8.034 \cdot \gamma^{0.648} \text{ Pa.} \tag{5}$$

Taking into account the studied rheological characteristics, the parameters of pipeline transport for the conditions of the most viscous mixture P-(CT)-6-75 have been analytically determined (Table 2). In calculating the transportation parameters, the main one is the performance of the backfill complex, which affects the choice of pipeline diameter and the optimal mixture movement rate, the amount of energy consumption and the choice of a pressure pump. The determining limiting element is the performance of the paste mixture mixer, which primarily determines the overall throughput of the complex. Given this, it is recommended to use a WAH08800 spiral-blade type mixer, capable of preparing a paste mixture with a maximum performance of up to 250 m³/h.

The determined technological parameters form the basis for further calculation of operating costs for pipeline transport of the paste backfill mixture, which depend on its rheological characteristics.

Table 2 – Parameters of the paste backfill mixture transportation

Parameter	Value
Backfill complex performance, m^3/h	240
Critical movement rate of the paste backfill mixture, m/s	1.36
Internal diameter of the pipeline, mm	240
Mixture shear rate in the pipeline, s^{-1},	51.6
Shear stress, Pa	125
Average height difference from tailings to cavities, m	15
Energy consumption for pumping the mixture, kWh/m^3	5.0
Required piston pump pressure, MPa	15
Maximum transportation length of the mixture, m	7000

At the same time, taking into account the maximum length of transportation allows the optimization model to set restrictions on the operation of one pump: after exceeding this threshold, operating costs increase due to the need to involve an additional booster pump.

It should be taken into account that the actual length of the pipeline may be slightly shorter than the calculated one due to the variability of terrain slopes, route features, the presence of turns, bends, constrictions, local resistance, which generally increases the overall hydraulic losses. To reduce hydraulic resistance in such conditions, it is advisable to add up to 1% of loam to the paste mixture by partially replacing the tailings, which, according to our previous studies, helps to reduce the flow resistance without reducing the strength characteristics of the monolithic backfill mass.

3.3. Study of the backfill complex location using the cost optimization method

To compile a cost optimization model in the context of choosing a rational location for a mobile backfill complex, it is necessary to quantify the cost components for both transport elements, namely, a conveyor line for feeding tailings and the pipeline network for transporting the paste mixture. Taking into account both capital and operating costs makes it possible to determine the economically feasible position of the complex at the maximum distance of the group of technogenic cavities from the tailings dump (group 3). In this regard, the following are expressions for determining the costs for each of the transport system links.

The total costs of a conveyor line are determined as follows:

$$Z_{conv}(X) = (C_{conv} + T \cdot E_{conv}) \cdot X \quad \text{UAH}, \qquad (6)$$

where C_{conv} – capital costs per 1 m of conveyor line, UAH/m; T – duration of backfilling operations, years; E_{conv} – operating costs per 1 m of conveyor line, UAH/(m·year); X – variable distance from the tailings dump to the backfill complex, m.

The total costs for pipeline transport are determined by the formula:

$$Z_{pip}(X) = \left(C_{pip} + T \cdot E_{pip}\right) \cdot \left(L_{total} - X\right) \text{ UAH,} \quad (7)$$

where C_{pip} – capital costs per 1 m of backfill pipeline, UAH/m; E_{pip} – operating costs per 1 m of backfill pipeline, UAH/(m·year); L_{total} – the total length of the transport route, m; ($L_{total} - X$) – variable distance from the backfill complex to the technogenic cavities, m.

Operating costs for electricity during the operation of conveyor transport will be as follow:

$$E_{conv} = P \cdot \tau \cdot d \cdot t \text{ UAH/(m·year),} \quad (8)$$

where P – is the determined performance per 1 m of the conveyor, with a motor power of 70 kW of the KL-800 conveyor for 1000 m is 0.07 kW/m; τ – load factor, $\tau = 0.8$; d – electricity tariff, $d = 4$ UAH/(kW·h); t – the number of hours of the backfill complex operation per year, $t = 5760$ hours.

To solve the optimization model of the most efficient location of the mobile backfill complex, technical-economic indicators were used, obtained in the course of research and adopted in the calculations (Table 3).

The value of operating costs E_{conv} for the entire length of horizontal conveyor transport is a step function that depends on the distance from the tailings dump to the backfill complex X. With an increase in the conveyor length by every 1000 m, due to the need to install a new drive, operating costs increase several times. Thus, E_{conv} is a segmented dependence that changes in a jump-like manner within certain intervals of length X:

$$E_{conv}(X)=\begin{cases}1290\,UAH/(m\cdot year), & 0<X\le 1000\\ 2580\,UAH/(m\cdot year), & 1000<X\le 2000\\ 3870\,UAH/(m\cdot year), & 2000<X\le 3000\\ 5160\,UAH/(m\cdot year), & 3000<X\le 4000\\ 6450\,UAH/(m\cdot year), & 4000<X\le 5000\\ 7740\,UAH/(m\cdot year), & 5000<X\le 6000\\ 9030\,UAH/(m\cdot year), & 6000<X\le 7000\\ 10320\,UAH/(m\cdot year), & 7000<X\le 8000\\ 11610\,UAH/(m\cdot year), & 8000<X\le 9000\\ 12900\,UAH/(m\cdot year), & 9000<X\le 10000\\ 14190\,UAH/(m\cdot year), & 10000<X\le 11000\\ 15480\,UAH/(m\cdot year), & 11000<X\le 12000\end{cases}, \quad (9)$$

The total costs for a conveyor line can be determined as follows:

$$Z_{pip}(X)=\left(C_{pip}+E_{pip}(X)\right)\cdot\left(L_{total}-X\right). \quad (10)$$

Table 3 – Constituent elements of the optimization model and their values

Model element	Value
Capital costs for horizontal closed-type conveyor KL-800, UAH/m	18000
Capital costs for the main and flushing pipelines, UAH/m	10000
Operating costs per 1000 m of tailings conveyor transport, UAH/(m·year)	1290
Operating costs for pipeline mixture transportation, UAH/(m·year): – at 1 piston pump – at 2 piston pumps	 5644 5644·(1.02…1.5)
The term of execution of backfilling operations, years	5
Length of the transport chain from the tailings dump to the technogenic cavities	0…12000
Maximum length of the mixture transportation when using 1 piston pump, m	7000

Operating costs for electricity during the operation of pipeline transport are determined by the following algorithm.

The volume of the paste backfill mixture in 1 m of pipeline is determined:

$$V = \pi \cdot \frac{D^2}{4} \quad \text{m}^3, \tag{11}$$

where V – volume of mixture in 1 m of pipe, m^3; D – internal diameter of the pipe, D = 0.219 m.

The energy consumption per 1 m of the backfill pipeline is as follows:

$$E = e \cdot V \quad \text{kW·h/m}^3, \tag{12}$$

where e – specific energy consumption for pumping 1 m^3 of a paste backfill mixture of 6% cement and 75% solid part with maximum rheological characteristics, e = 5 kW·h/m^3.

Operating costs for electricity per 1 m of pipeline are determined as follows:

$$E_e = e \cdot V \cdot d \cdot T \quad \text{UAH/m}. \tag{13}$$

Operating costs of the pipeline, taking into account the number of pumps can be determined using the expression:

$$E_{pip}(X) = \begin{cases} E_{pip}, & L_{total} - X \le 7000 \ (1 \ pump) \\ k \cdot E_{pip}, & L_{total} - X > 7000 \ (2 \ pumps) \end{cases} = \begin{cases} E_{pip}, & X \ge 5000 \\ 2E_{pip}, & X < 5000 \end{cases}, \tag{14}$$

where k – a coefficient that takes into account an increase in energy consumption during the operation of the second booster pump after exceeding L_{max}.

After reaching the maximum length of effective transportation of the paste mixture with one pump (L_{max} = 7000 m), further increase in the pipeline section requires the installation of an additional pump. In this case, electricity costs increase unevenly, as the second pump consumes energy only for a part of the route that exceeds 7000 m. Therefore, the growth coefficient of operating costs k changes gradually, from 1.02 to 1.5 every 200 m (within 7000...12000 m). The coefficient value is calculated proportionally to the second section length and the first pump specific consumption.

As a result of the modeling, when the length of the horizontal conveyor line X and the pipeline transport ($L_{total} - X$) changes, graphs of changes in their total costs separately and the cumulative total costs (Fig. 5) have been obtained.

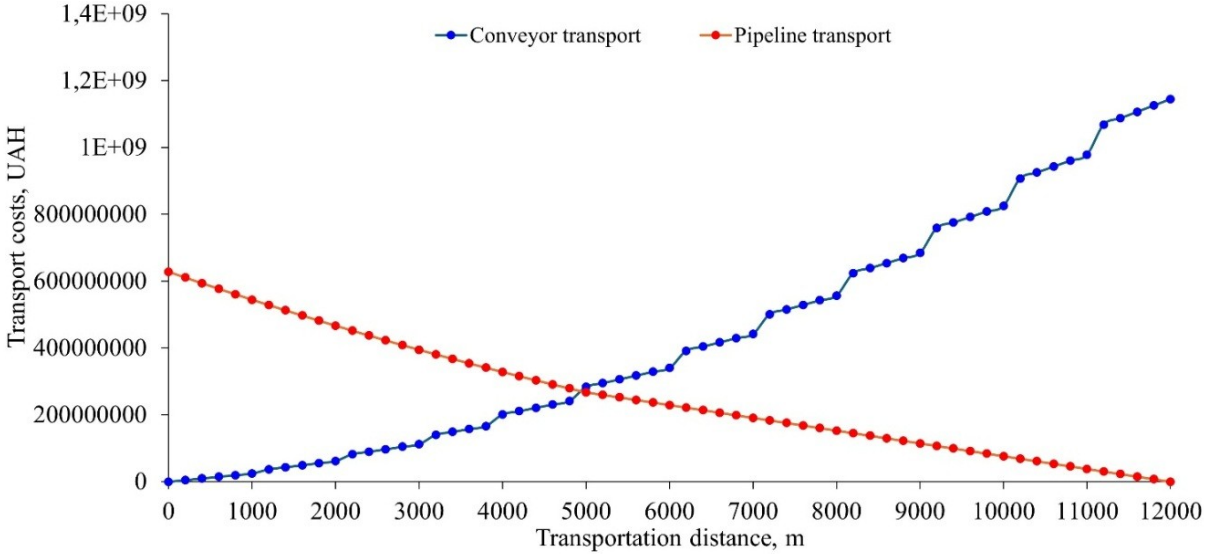


Figure 5 – Dependences of changes in total costs for conveyor and pipeline transport depending on the length of transportation

Figure 5 analysis demonstrates the economic assessment of the mutual substitutability of conveyor and pipeline transport within the total length of the transport route from the tailings dump to technogenic cavities of 12000 m. With the increase in the conveyor line length, there is a proportional decrease in the pipeline transport length. So, for example, with a conveyor line length of 2000 m, the pipeline transport length will be 10000 m, and the total costs will be UAH 61.8 million and UAH 466.8 million, respectively. This principle can be used to estimate economic costs for certain lengths of conveyor and pipeline transport within the total length of the 12000 m route. This graph construction (Fig. 5) allows us to study the peculiarities of the relationship of economic costs between two technological transport options, which are studied within the same general transportation scheme. Thus, the obtained dependences make it possible to determine, at what length of one type of transport costs exceed the costs of another, and in the future to optimize the point of the backfill complex placement depending on the technical-economic conditions. Equality of costs for both types of transport is observed at a length of 4900 m for conveyor transport and 7100 m for pipeline transport. The found equality indicates only the intersection point of the two cost curves, but is not yet an optimum in the general economic sense. That is, it is only the balance limit, up to which the pipeline transport costs exceed those of conveyor transport, and beyond which conveyor transport is more expensive than pipeline transport.

It should be noted that the non-linear (quadratic) nature of the increase in conveyor transport costs is conditioned by the fact that the length of the line is taken into account twice: linearly in total costs per 1 m, and secondly in operating costs, which increase proportionally with length and are additionally multiplied by the same length. As a result, the formula gives a quadratic expression (X^2), which causes an accelerated, convex increase in total costs for conveyor transport.

As a result of summing up the costs for conveyor and pipeline transport, their dependence on the maximum length of the transport route was constructed according to the optimization model, which aims to identify the minimum (Fig. 6).

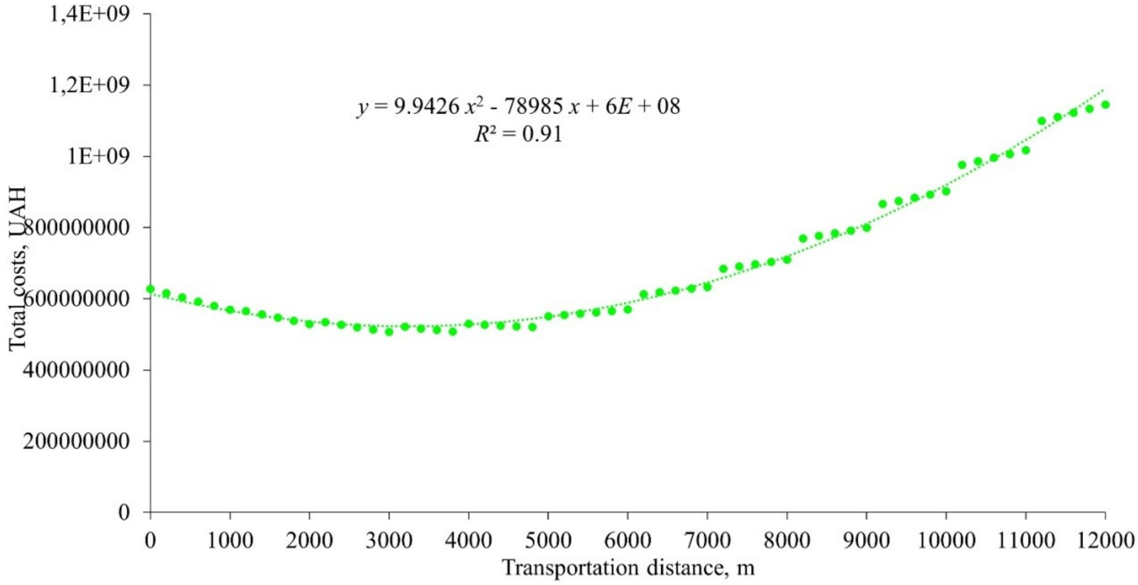


Figure 6 – Dependence of total transport costs depending on the length of transportation

Figure 6 analysis shows that the total costs of transporting the backfill mixture have a clearly expressed parabolic nature and are described by a quadratic function that reaches a minimum at a conveyor transport length of about 4000 m. This means that with a variable distribution of costs between two alternative types of transport (conveyor and pipeline) and a total route length of 12000 m, there is an optimal ratio that provides a minimum of total costs. The minimum of the function 4000 m is the point where the increase in costs for further lengthening of one type of transport exceeds the savings from the reduction of the other, and it is this point that is the economically most expedient location of the backfill complex. It is also advisable to identify a rational range of minimum costs, which is in the range of 3300–4700 m.

Since the conveyor transport is laid from the tailings dump to the backfill complex for moving of beneficiation tailings, its optimal length actually determines the rational location of the complex relative to the tailings dump. Thus, the distance of 3300–4700 m is an economically feasible range for placement of the backfill complex, where the total transportation costs remain close to the minimum value. The difference between the intersection point of costs for different types of transport (4900 m) in Figure 5 and the optimum point (4000 m) in Figure 5 is explained by the fact that the intersection of the cost curves reflects only the equality of the costs of individual types of transport systems, but does not take into account the form of their changes with length, while the total costs depend precisely on the rate of growth of each system costs. Taken together, the dependences obtained (Figs. 5, 6) provide a technical-economic basis for selecting a rational option for placing the backfill complex between the tailings dump and technogenic cavities, and taking into account the topographic situation and the configuration of the transport route itself.

The conducted studies of the rational placement of the mobile backfill complex made it possible to clarify the scheme of transporting the paste mixture with the movement of mobile backfill complex to the priority technogenic cavities of groups 1, 2 and 3, which is shown in Figure 7. The developed scheme for transporting a paste backfill mixture using a mobile backfill complex (Fig. 7) takes into account the topographic peculiarities of the territory and the results of technical-economic modeling of the optimal placement of the complex.

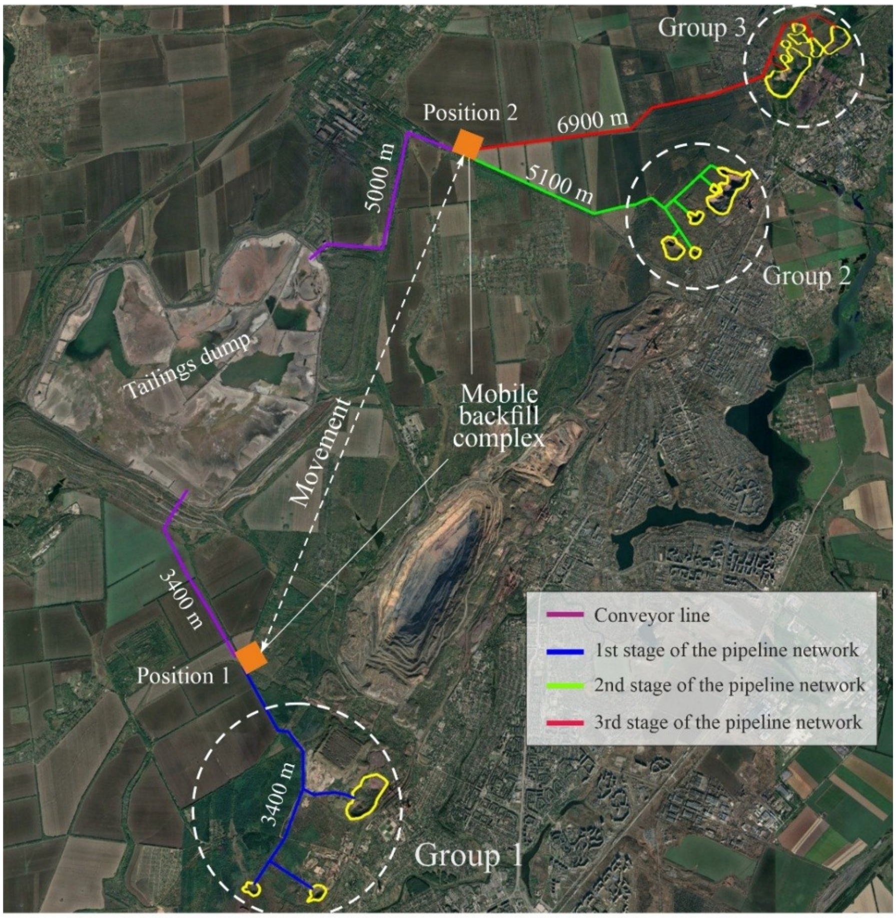


Figure 7 – System for transporting paste backfill mixture to technogenic cavities using a mobile backfill complex

Thus, two expedient positions for placing a mobile backfill complex have been identified: position 1 at a distance of 3400 m from the tailings dump to fill group 1 technogenic cavities, and position 2 at a distance of 5000 m – to fill groups 2 and 3 technogenic cavities. It should be noted that the distances from the tailings dump to the adopted positions 1 and 2 of the backfill complex are almost within the rational range of 3300–4700 m, set analytically as a zone of minimal total transportation costs. Determining the optimal location of the complex makes it possible to accurately form the quantitative technological transportation system parameters, namely the length of the conveyor line from the tailings dump to the backfill complex and each stage of the backfill pipeline network from the complex to technogenic cavities.

This is necessary for a full further ecological and economic assessment of the elimination of cavities based on the paste backfilling technology.

Further research should include determining the ecological and economic assessment of the application of the proposed concept of eliminating technogenic cavities based on paste backfilling; comparing options for individual elimination of certain cavities (specific mine failures, closed quarries) or complex elimination of all formed cavities. The economic benefit of eliminating cavities will be to restore the earth's surface over the quarry cavities and return it to the industrial-economic potential of the city of Kryvyi Rih, thereby preventing material damage from the gradual expansion of mine failure zones and sudden caving of the earth's surface over unfilled underground cavities.

4. Conclusions

As a result of the research, the scientific and practical results have been obtained:

1. The expediency of using the Herschel-Bulkley model to describe the rheological behavior of paste mixtures based on experimental "shear stress – shear rate" curves has been proved. The Herschel-Bulkley rheological models for paste backfill mixtures with a solid part content of 73–75%, made from coarse iron-ore beneficiation tailings, have been specified. The determined model parameters (yield strength, consistency coefficient and flow index) allow for correct prediction of the mixture behavior and determination of pipeline transport parameters.

2. A model for optimizing the total costs for transporting the paste mixture from the tailings dump to technogenic cavities using a combined scheme (conveyor + pipeline) has been developed. The influence of the variable distance to the mobile backfill complex on capital and operating costs of conveyor and pipeline transport is substantiated.

3. It has been found that the dependence of total transportation costs is parabolic in nature with a minimum at the distance of backfill complex from the tailings dump in the range of 3300–4700 m for the conditions of the Kryvyi Rih Iron-ore Basin. This corresponds to a rational ratio of the lengths of the conveyor and pipeline sections, which allows achieving an economic balance between the costs for laying and operating both transport lines.

4. The rational positions for initial placement and subsequent movement of the mobile backfill complex have been determined, taking into account the spatial position of groups of technogenic cavities, and the optimal conveyor and pipeline route has been specified, which allows for effective elimination of cavities with minimal costs.

Conflict of interest

Authors state no conflict of interest.

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ОБҐРУНТУВАННЯ РАЦІОНАЛЬНОГО РОЗМІЩЕННЯ ЗАКЛАДНОГО КОМПЛЕКСУ ПРИ ЛІКВІДАЦІЇ ТЕХНОГЕННИХ ПУСТОТ ЗАЛІЗОРУДНИХ РОДОВИЩ НА ОСНОВІ ТЕХНОЛОГІЇ ПАСТОВОГО ЗАКЛАДАННЯ

Петльований М.

Анотація. Обґрунтування раціонального розміщення закладного комплексу для забезпечення ефективної ліквідації техногенних пустот, утворених внаслідок підземної та відкритої розробки залізорудних родовищ, з урахуванням реологічних властивостей пастоподібних закладних сумішей та мінімізації транспортних витрат. У дослідженні застосовано експериментальний метод, що включає приготування пастоподібних сумішей із вмістом твердого 73–75% та дослідження їх реологічних характеристики на цифровому ротаційному віскозиметрі NDJ-8AT. Також застосовано метод техніко-економічного моделювання для оцінки капітальних і експлуатаційних витрат на транспортування пастової суміші трубопроводом і конвеєром залежно від змінної відстані між хвостосховищем і закладним комплексом, а також для визначення його оптимального розміщення шляхом мінімізації сумарних витрат. Доведено доцільність застосування моделі Гершеля-Баклі для опису реологічної поведінки пастових закладних сумішей на основі хвостів збагачення, що складають основу визначення комплексу параметрів їх транспортування трубопровідним транспортом. Встановлено, що сумарні витрати на транспортування мають параболічний характер і сягають мінімуму при балансі довжин трубопроводу та конвеєра, що дозволило визначити оптимальну зону розміщення мобільного закладного комплексу, яка знаходиться в межах 3300–4700 м від хвостосховища. Рекомендовано раціональні місця розташування та позиції переміщення мобільного закладного комплексу між групами техногенних пустот. Уточнено реологічні моделі Гершеля-Баклі для пастових закладних сумішей із вмістом твердого 73–75%, виготовлених з крупних хвостів збагачення залізних руд. Вперше запропоновано комплексну модель оптимізації розміщення мобільного закладного комплексу з урахуванням реологічних властивостей суміші та комбінованого транспортування. Результати корисні при застосуванні концепції ліквідації техногенних пустот у залізорудних регіонах, а саме, при плануванні розміщення мобільного закладного комплексу для ліквідації техногенних пустот, зокрема у Криворізькому басейні. Реалізація концепції дозволяє покращити стан довкілля через утилізацію хвостів збагачення, блокувати розвиток деформацій земної поверхні й повною мірою відновити порушені земельні площі.

Ключові слова: техногенні пустоти, залізорудні родовища, концепція, хвости збагачення, пастове закладання, оптимізація, мінімізація, витрати.