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Studying the geotechnical stability of the earth's surface during the formation of different backfill mass types in quarry cavities

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Abstract. The research focuses on studying the geotechnical stability of backfill mass in the mined-out spaces of inactive quarries for restoring the earth's surface in the conditions of the Kryvyi Rih region, where large-scale complex iron ore mining is conducted. Based on the analysis, it has been determined that in the region, to fill inactive quarry cavities and failure zones, the traditional method of filling them with dump waste rock is used. Given that the city of Kryvyi Rih is a densely populated ,highly indutrialised agglomeration, the restoration of additional land areas could bring significant benefits for the economic development of the region, but the rock mass is not able to provide reliable geomechanical stability of the earth's surface. The transformation of the physical state of the backfill mass from a loose to a monolithic state is proposed. In order to select alternative backfill methods, the quantitative and qualitative structure of the accumulated wastes of the mining-metallurgical complex that can be used as backfill materials is analyzed. Taking into account the significant volumes of accumulated beneficiation tailings and their limited utilization, it is recommended to use them as part of cemented paste backfilling, which will lead to an improvement in the environmental situation. The research methodology consists of laboratory tests of physical-mechanical properties of dump hard rocks, analysis of the properties of paste backfilling, and numerical modeling of stability of various types of backfill masses. It has been found that the mixture of rocks of 0...100 mm in terms of bulk density and voidness is close to the minimum fraction of 0...5 mm, which does not require the need to select a certain fractional composition. A «stress-strain» curve of a 0...100 mm rock mixture with a logarithmic relationship, characterized by three stages of strain, has been plotted. The strain modulus value has been calculated. The similarity of the mechanical characteristics of the studied mixture to the full-scale characteristics of dump hard rocks is substantiated. The modeling results show that the maximum strains in the case of rock backfilling reach 780 mm, while the calculations of paste backfilling show a significant decrease in the subsidence value, reaching only 43 mm. The difference in the values of subsidence is due to a significant difference in physical-mechanical properties. Based on studying the hardening conditions of paste backfill mixtures and temperature dynamics in the region, a seasonal approach and the formation of a combined backfill mass are proposed to maintain the reclamation rate. The research findings are valuable for the development of the construction direction of reclamation in the Kryvyi Rih region and the rational use of restored land areas.

Keywords: quarry cavities, geomechanical stability, strain properties, loose rock backfilling, cemented paste backfilling, combined approach

Дослідження геотехнічної стійкості земної поверхні при формуванні різних видів закладного масиву у кар'єрних пустотах

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Анотація. Дослідження фокусується на вивченні геотехнічної стійкості закладних масивів у вироблених просторах недіючих кар'єрів для відновлення земної поверхні в умовах Криворізького регіону, де у великих масштабах здійснюється комплексний видобуток залізних руд. Аналізом визначено, що у регіоні для заповнення недіючих кар'єрних пустот та провальних зон застосовується їх традиційне засипання пустими відвальними породами. Враховуючи, що м. Кривий Ріг є потужною індустріальною агломерацією з густим населенням відновлення додаткових земельних площ могло б принести значну користь для економічного розвитку регіону, проте породний масив не здатен забезпечити надійну геомеханічну стабільність земної поверхні. Запропоновано трансформацію фізичного стану закладного масиву з сипкого до монолітного. Для вибору альтернативних методів закладання здійснено аналіз кількісно-якісної структури накопичених відходів гірничо-металургійного комплексу, що можуть бути використані як закладні матеріали. З урахуванням значних обсягів накопичення хвостів збагачення, обмеженості їх утилізації, рекомендовано їх використовувати у складі цементованого пастового закладання, що призведе до поліпшення екологічного стану. Методологія дослідження складається з лабораторних досліджень фізико-механічних властивостей скельних відвальних порід, аналізу властивостей пастового закладання й чисельного моделювання стійкості різних видів закладних масивів. Встановлено, що суміш порід 0…100 мм за характером насипної щільності й пустотності близька до мінімальної фракції 0…5 мм, що не потребує необхідності підбору певного фракційного складу. Побудовано криву «напруження-деформація» суміші порід 0…100 мм, які мають логарифмічний зв'язок, характеризується трьома стадіями деформування. Визначено величину модуля деформації. Обґрунтовано подібність механічних характеристик досліджуваної суміші натурним характеристикам відвальних скельних порід. Результати моделювання показують, що при породному закладанні максимальні деформації сягають 780 мм, а розрахунки пастового закладання показують суттєве зменшення величини осідання, сягаючи тільки 43 мм. Різниця у величинах осідання пов'язана з суттєвою відмінністю у фізико-механічних властивостях. На підставі вивчення умов тверділня пастових закладних сумішей й динаміки температур у регіоні й для збереження темпів рекультивації запропоновано сезонний підхід й формування комбінованого закладного масиву. Результати досліджень є цінними для розвитку будівельного напряму рекультивації у Криворізькому регіоні й раціонального використання відновлених земельних площ.

Ключові слова: кар'єрні пустоти, геомеханічна стабільність, деформаційні властивості, сипке породне закладання, цементоване пастове закладання, комбінований підхід

Introduction

Today, humanity uses mineral resources on a large scale, driven by population growth and, consequently, an increase in the need for various infrastructure, goods and services (Ericsson & Löf, 2019; Maja & Ayano, 2021; Petlovanyi et al., 2023a). Thus, according to some estimates, more than 150 billion tons of rock mass are mined in the world to obtain important types of mineral raw materials, of which about 60-65 billion tons of minerals are obtained, with 72 billion tons of waste rock and 13 billion tons of beneficiation tailings generated (Franks, Keenan, Tonda, & Kariuki, 2022). Significant rates of mining various mineral resources on the planet have led to significant changes in the natural environment (Gorman & Dzombak, 2018; Bosak, Popovych, Stepova, & Dudyn, 2020; Sonderegger et al., 2020), with the upper lithosphere experiencing particularly critical damage due to rock mass extraction and deformation of the earth's surface (Dudek et al., 2022; Petlovanyi, Malashkevych, Sai, & Stoliarska, 2023). Thus, scientists around the world have conducted a large-scale inventory of 44,929 objects of large-scale, as well as artisanal and small-scale mining facilities, including quarries, mines, tailings dumps, waste rock dumps, technical reservoirs, processing plants and other facilities related to mining activities (Maus et al., 2022). It has been revealed that the mentioned facilities occupy 101,583 km^2 of land area. According to other estimates, the potential impact of mining facilities, assuming that it extends 50 km from mining sites, is about 50 million km^2. Given the rapid increase in the population of different countries of the world and the growing demand for land areas, which has increased significantly over the past 30 years (Sonter, Dade, Watson, & Valenta, 2020), the problem of restoring the earth's surface for its further reasonable use has become increasingly important.

In the context of a significant destructive environmental impact of mineral resource mining processes, the use of «green mining technologies» is becoming increasingly important, as they minimize environmental pollution and improve economic performance (Wu, Zhao, & Li, 2022; Onifade et al., 2024). One of the most important technologies is the backfilling of the mined-out space during the mining process, which solves a set of problems: allows recycling industrial waste accumulated on the earth's surface, prevents the dangerous development of the earth's surface deformations and creates favourable geomechanical conditions for mining in a complex geological environment (Chiloane & Mulenga, 2023; Feng et al., 2023; Kuzmenko et al., 2023). However, due to the increased economic costs of backfilling operations, they are usually used only when it is absolutely necessary, such as mining under objects of industrial and civil infrastructure, as well as high value mineral resources. The use of backfill technologies in the conditions of open technogenic cavities has not been sufficiently studied and is of significant scientific interest for further research.

In the context of open-pit mining, depleted quarries are usually reclaimed using forestry, water management, and recreational reclamation methods (Hendrychová, Svobodova, & Kabrna, 2020; Pratiwi et al., 2021; Zine et al., 2024). However, when using these methods, the earth's surface level is not restored. In urbanized industrial centres, the restored land area at the quarry site could be rationally used precisely for the development of industrial and economic potential, such as the construction of promising industrial or civil infrastructure facilities. During the construction of such facilities, high geotechnical requirements are imposed on the restored earth's surface, as the safety factor is the highest priority today.

Ukraine ranks 20th in the world in terms of land area occupied by mining activities, which is estimated by foreign scientists to be about 600 km^2 (Maus et al., 2022), which correlates with government statistical data (National report…, 2022). Thus, the area of land under mining facilities is estimated at 530 km^2, of which 45% is in Dnipropetrovsk Oblast, 11% in Donetsk Oblast, 8% in Zhytomyr Oblast, and 6% in Poltava Oblast. In 2021, 17.35 hectares of disturbed land were reclaimed, of which more than 82.7% (14.35 hectares) are agricultural land. The total area of land under reclamation reaches more than 7 thousand hectares. An analysis by the type of mineral resource mining in oblasts has revealed that the earth's surface is most affected by iron ore mining in the city of Kryvyi Rih, around which is the largest area of allotted and disturbed land by quarries and mines, and the largest concentration of volumes of waste accumulation from the mining, processing and metallurgical industries (Bazaluk et al., 2024). Significant technogenic and ecological problems of the Kryvyi Rih region have been noted in many studies (Kalinichenko, Dolgikh, Dolgikh, & Pysmennyi, 2020; Koptieva & Denysyk, 2021; Batur & Babii, 2022; Savosko, Bielyk, Lykholat, & Heilmeier, 2022). Some scientists link the technogenic changes in the geological environment of the region, caused by intensive iron ore mining in Kryvbas, to seismic activity that has been periodically occurring in the region recently. The research results of scientists indicate an urgent need to apply new approaches to technologies that can restore or improve the earth's surface state, as well as intensify waste management.

Today, in the Kryvyi Rih Basin, the reclamation of closed quarries and failure zones is based on filling their space with dump waste rock, but insufficient research has been conducted on the geotechnical stability of the surface of the formed backfill mass, which is a loose medium. The filled-up rock backfill mass is characterised by its voidness, high filtration properties and ability to self-compaction under the action of gravity, which does not guarantee surface stability and limits its intended use. The region also needs a new concept of restoring the earth's surface, disturbed by mining operations, through the use of alternative technologies for backfilling open technogenic cavities, which would eliminate the disadvantages of traditional waste rock filling and for which there are optimal conditions.

The presented research is aimed at studying the physical-mechanical characteristics of dump hard rocks as a backfill material and predicting the surface subsidence of a loose rock backfill mass. Attention is also paid to an alternative option, which involves the formation of a monolithic backfill mass and assessment of its geotechnical efficiency, which is an innovative approach to achieving the earth's surface stability and improving the environmental situation in the Kryvyi Rih Basin.

Existing and proposed approaches to reclamation of severely disturbed earth's surface

Today, in the Kryvyi Rih region, as part of the implementation of the municipal environmental program, designed to improve the environmental situation, a number of old closed quarries and failure zones within the mining allotments of Yuvileina, Frunze, Kryvorizka, Kozatska and Ternivska mines are filled with dump waste rock. In terms of improving the ecological situation, these reclamation measures are definitely useful, as they enable the utilization of some of the dump rocks accumulated in the region during iron ore mining. On the other hand, with the traditional filling of mined-out quarry areas with dump waste rocks, there are restrictions in the further use of the restored land area imposed by the safety factor. For example, when filling the No. 2 quarry of PJSC Central Iron Ore Enrichment Works, a new waste rock dump is planned to be placed on the restored land area. Given that the city of Kryvyi Rih is a powerful industrial agglomeration with a population of about 700 thousand, the restoration and introduction of additional land areas could bring significant benefits for the economic development of the region. An important task is to ensure the long-term geomechanical earth's surface stability.

It is advisable to revise the concept of the mining-technical reclamation stage of quarry cavities in the direction of transformation from a loose mass to a monolithic artificial backfill mass, as shown in Figure 1.

Based on the global experience in conducting backfilling operations in underground mining of deposits, the following backfill methods can be distinguished, in which a monolithic hardened mass is formed: cemented paste backfilling, cemented rock backfilling, injection rock backfilling (Kuzmenko & Petlovanyi, 2015; Ghirian & Fall, 2017; Petlovanyi, Malashkevych, & Sai, 2020; Zhang et al., 2022.

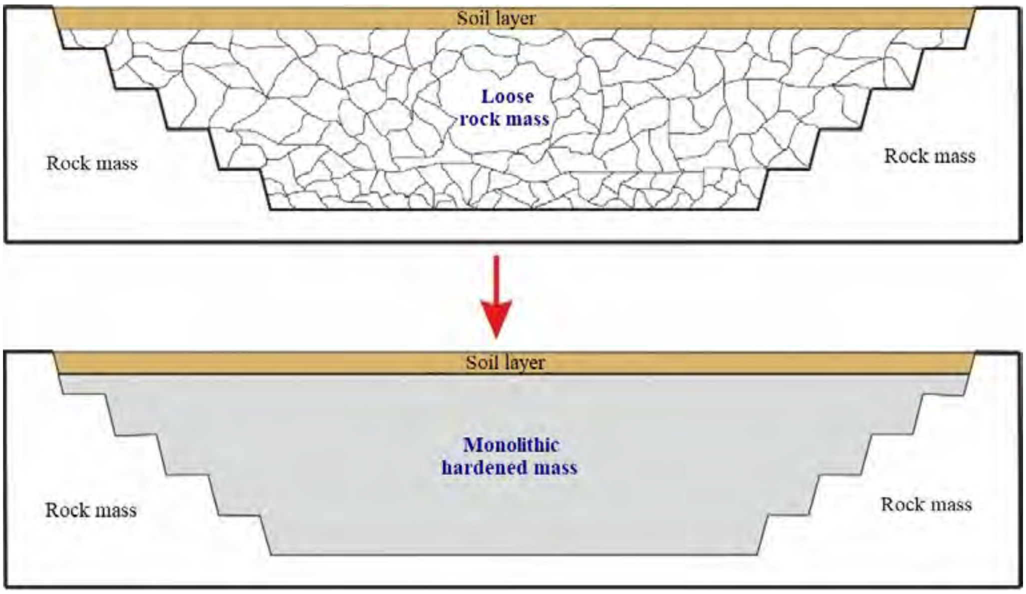


Fig. 1. Schematic representation of the backfill mass physical state transformation when filling quarry cavities

To consider these technologies as an alternative to loose mass for backfilling technogenic cavities in the Kryvyi Rih region, it is necessary to study the diversity of mineral and raw material base of backfill materials accumulated in the Kryvyi Rih region, which are usually industrial wastes. Thus, according to statistics from the Dnipropetrovska Oblast, about 10.7 billion tons of waste from the mining and metallurgical complex have been accumulated around and in the city of Kryvyi Rih. A detailed analysis of the volumes and types of accumulated main industrial waste is shown in Figure 2.

Thus, the Kryvyi Rih region has the largest accumulation of dump waste rocks from quarries and mines, as well as finely dispersed beneficiation tailings. The share of generated waste utilization is 25-35%, with a wider range of utilization of dump waste rocks, including the construction of quarry roads and tailings dumps, crushed stone and reclamation material production. Beneficiation tailings are mostly utilized only in the construction of dams and tailings dumps. Given the significant dust pollution of the environment by dry beaches of tailings dumps (Park, Kim, Lee, & Kim, 2019; Thompson, McDonald, Kelcey, & Dixon, 2021), this type of waste requires more attention for the development of alternative directions for its utilization. Such a direction can be the use of finely dispersed beneficiation tailings as the main component in cemented paste backfilling to fill open technogenic cavities, such as inactive quarries and failure zones. Filling of open technogenic cavities does not require high physical-mechanical characteristics of paste backfilling, as in underground mining, due to the absence of rock pressure impact, but it should be sufficient for the construction of infrastructure facilities on the restored surface.

To better understand the differences between traditional loose rock backfilling used in the region and cemented paste backfilling, Table 1 outlines the strengths and weaknesses of the technologies as elements of SWOT-analysis. Table 1 analysis shows that the highest quality of the backfill mass in techno-

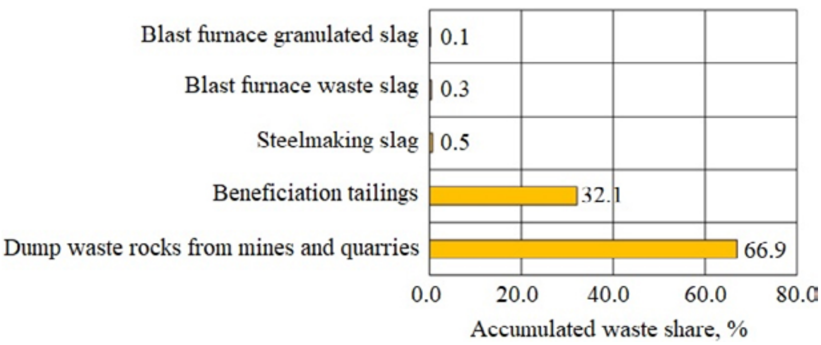


Fig. 2. Structure of accumulated waste from the mining and metallurgical complex in the city of Kryvyi Rih

Table 1. Results of the comparison of loose rock and paste backfilling using the SWOT-analysis elements

S-strengths	W-weaknesses
Loose rock backfill mass	
• easy execution of technological processes; • relative cheapness of backfilling operations; • dump waste rock utilization.	• dust pollution during waste rock filling; • high voidness and filtration properties of the mass; • the probability of increased mass shrinkage; • a long time for the mass to shrink; • limited use of the restored earth's surface.
Cemented paste backfilling	
• high quality and homogeneity of the backfill mass; • low filtration properties of the mass; • utilization of a wide range of industrial waste (tailings, metallurgical slag, fly ash, etc.); • environmental friendliness of the mass formation technology; • minimal mass shrinkage; • wide variability of the use of the restored earth's surface.	• relatively high investment and cost of backfilling operations; • the impact of climate conditions on the backfilling operations; • greater complexity of the execution of technological processes.

genic cavities can be achieved precisely when using cemented paste backfilling, the weaknesses of which are relatively high economic costs and the influence of climate conditions.

Mechanisms for eliminating these weaknesses can be achieved through the distribution of investment funds of interested parties and scientific studies of optimal properties and specific organization participating in the operations of paste backfilling.

One of the most important criteria for backfill masses of open technogenic cavities is the stability and safety of the restored earth's surface. Therefore, a geomechanical assessment of the stability of the earth's surface restored using traditional waste rock backfilling and cemented paste backfilling is necessary to demonstrate the differences and effectiveness of each method.

Research materials and methods

To study the backfill mass formation, the iron ore quarries No. 2 and No. 4 of the former K. Liebknecht Ore Mining Administration on the western outskirts of the city of Kryvyi Rih, which were closed in the middle of the 20th century, were chosen, over which the earth's surface has not yet been restored (Fig. 3). The quarries were closely spaced, eventually combined and presented as a single quarry. These technogenic cavities have been identified as promising for restoring the earth's surface level. The quarries mined martite ore from the Parallel Quarry No. 2 deposit of the sixth ferruginous horizon $k_2^{6з}$, which outcropped to the earth's surface.

Using the Google Earth toolkit, the following parameters have been determined: length – 500 m, width – 270 m, maximum depth – 57 m. The earth's surface area that can be restored on the mined-out space of the quarry when it is backfilled is 21 hectares. The quarry on the northern side is partially filled with waste rock from the iron ore mine as rocks are formed during driving of mine workings. Dump trucks unload waste rock from the upper bench into the mined-out space of the quarry.

To accelerate the reclamation rate of the quarry cavity, the hard rocks from the Gleiuvatskyi Quarry No. 1 dump, located 250 m northwest of the quarry, can be used as the backfill material for quarry cavity.

The research is focused on the study of the surface subsidence value of the backfill mass from loose dump waste rocks, formed in the mined-out space of the abandoned quarries of the K. Liebknecht Ore Mining Administration in order to restore the earth's surface and geomechanically assess its state for further rational use.

To achieve this purpose, the research is conducted in two stages:

1) studying the physical-mechanical properties of hard rocks as a backfill material based on laboratory research and analysis of scientific papers;
2) performing numerical modeling by finite element method of the backfill mass surface subsidence values.

To simulate the backfill material, a hard rock sample was taken from one of the dumps of the mining-processing plant, and some of their characteristics are given in Table 2.

Hard rocks used in the research are similar in physical-mechanical characteristics to the dump rocks of Gleiuvatskyi Quarry No. 1.

The accepted granulometric composition of dump hard rock is based on the average granulo-

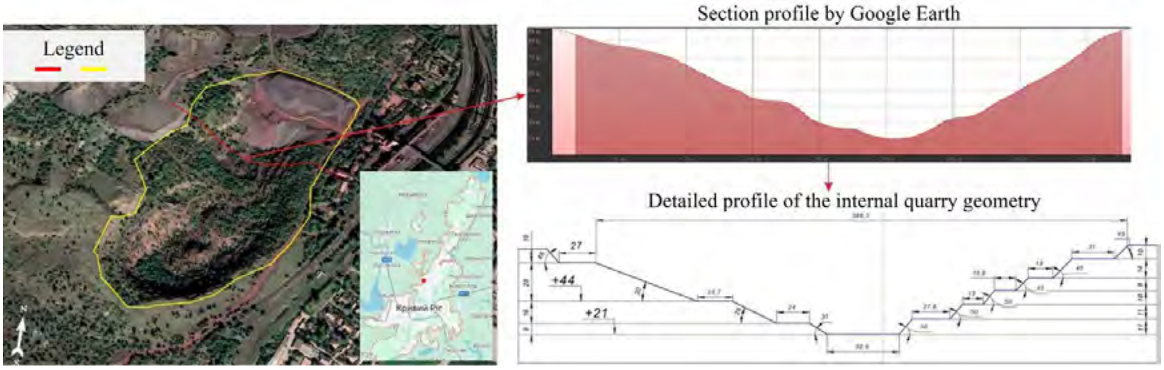


Fig. 3. Illustration of the quarry location and its width section: — selected quarry section; — quarry outline

Table 2. Initial data of sampled dump hard rocks

Parameter	Value
Lithological composition of the mixture	Quartzites, shales, amphibolites
Granulometric composition	0…100 mm
Average unit specific gravity of rocks, tons/m^3	2.8-3.0
Rock hardness by Prof. Protodyakonov's scale	10-12

metric composition of the rock mass after blasting operations at a number of quarries in the Kryvyi Rih region, according to the studies of (Peregudov & Peregudov, 2016; Zuevska, Ishchenko, Ishchenko, & Korobiychuk, 2021): 1000…500 mm – 7%; 500…400 mm – 9%; 400…300 mm – 9%, 300…200 mm – 15%; 200…0 mm – 60%. For the convenience of conducting laboratory tests, the fractions were reduced to a scale of 1:10, so a mixture of rocks in the range of 0...100 mm was studied while maintaining the proportionality of the granulometric composition of dump waste rock. The structural-logical scheme for laboratory testing of rock properties is shown in Figure 4.

To determine the physical-mechanical properties of hard rocks, a granulometric analysis of the selected rock samples was conducted using an ACB-300U sieve analyzer, a SNOL-type drying cabinet, a WLC 20/C/1 laboratory electronic balance, a cone for measuring the natural slope angle, and a set of KP-601/4 measuring vessels for determining the bulk density. Both separate rock fractions and a mixture of 0...100 mm fractions were studied. The voidness of individual fractions and the mass was assessed using known methods (Iordanov et al., 2020; Petlovanyi et al., 2021). The strain characteristics of 0...100 mm thick hard rocks as a backfill material were studied on a KS-200 laboratory press (Italy). A cylindrical metal vessel with a length of 25 cm and an internal diameter of 14 cm was made. The test rock mixture was poured into the vessel and a load in the range of 0...100 kN or a pressure of 0...6.5 MPa was applied, taking into account the sample area. According to the research results, the strain modulus E of the rock mixture was determined according to the generally accepted methodology, when the shrinkage of rock samples in the cylinder under load ceased to increase significantly and actually reached the maximum compaction state:

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

where:
$\Delta F = F_2 - F_1$ – is the difference between the 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.

To study the geomechanical stability of the backfill mass surface, a numerical modelling by the finite element method is used (Petlovanyi, 2016; Bondarenko et al., 2020; Sakhno, Sakhno, & Skyrda, 2022), which is implemented in the Solid Works software package. The geomechanical model is studied in a static mode and consists of a rock mass of the quarry cavity base and a loose mass from dump hard rocks (Fig. 5). The dimensions of the model are not decisive, since the rock mass elasticity modulus has a high value, and the object of research is precisely the backfill mass. Additionally, the earth's surface subsidence is studied when filling the quarry cavity with

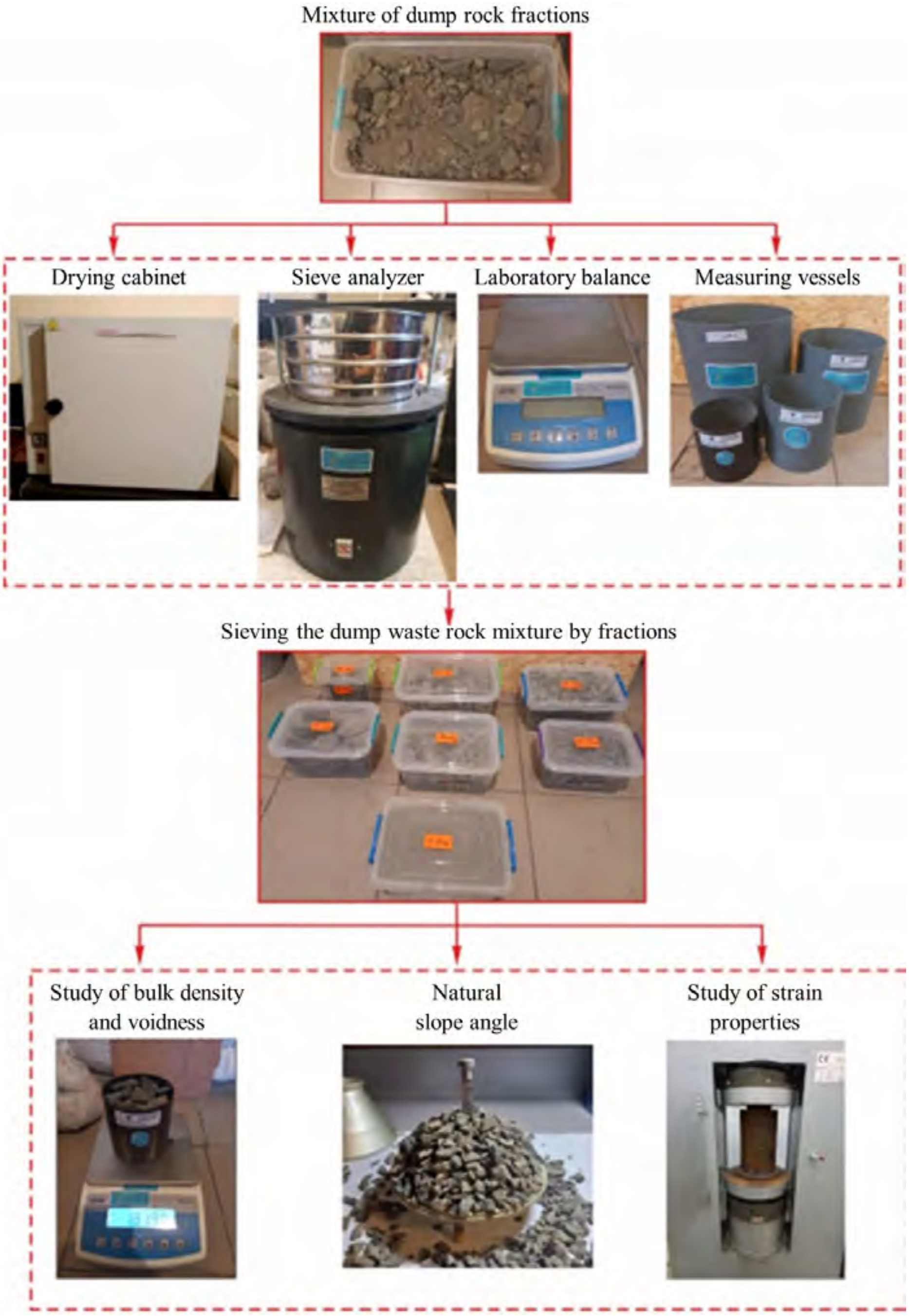


Fig. 4. Structural-logical scheme for determining the main physical-mechanical characteristics of dump hard rocks

paste monolithic backfill as an alternative option. A simplification of the quarry cavity model geometry is adopted, which will not significantly influence the process physics and the subsidence values. The chosen Drucker-Prager model type is the one that best describes the behaviour of loose and plastic materials, which can be exposed to both shear strains and volumetric changes. The linear elastic model with the Mohr-Coulomb (MC) failure criterion is most commonly used for paste backfilling. The model is rigidly fixed at the bottom and movable fixation is applied on the sides. The gravity action is specified in the model ($g = 9.81$ m/s^2). At 40 m intervals, 5 monitoring points are located on the backfill mass surface to record subsidence values.

The physical-mechanical characteristics of the model elements are given in Tables 3 and 4 and are specified as follows: rock mass – from geological reports of the field, rock backfilling – based on the performed laboratory tests; paste backfilling – based on scientific research of scientists, where the cemented paste backfilling includes iron ore beneficiation tailings, which, as a result of long-term hardening, reaches a stable strength of 3.0 MPa (Yilmaz, Benzaazoua,

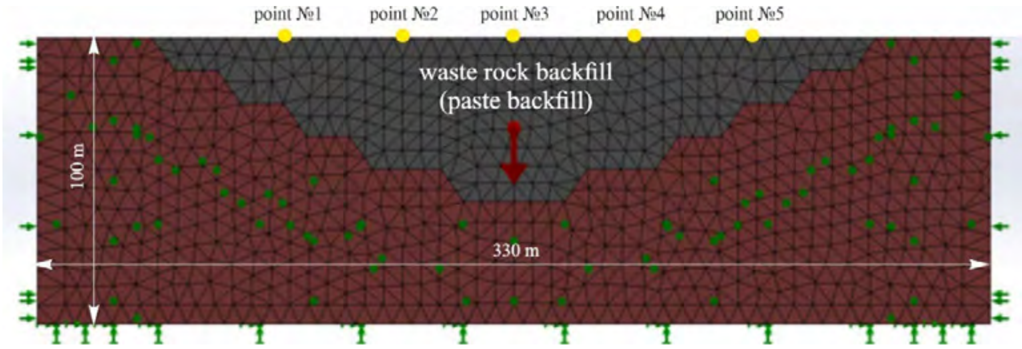


Fig. 5. Geomechanical model with grid of broken finite elements

Belem, & Bussière, 2009; Deng et al., 2017; Grabinsky, Jafari, & Pan, 2022; He et al., 2023).

Based on the research results, the curve of vertical strains and displacements is analyzed and the value of the backfill mass surface subsidence for loose rock and paste backfilling is assessed and compared.

Research results

Bulk density of loose backfill materials, including rock backfill masses, is an important indicator that determines their voidness, compaction capacity and strain properties. As a result of processing the laboratory data, the dependencies of changes in bulk density and voidness values depending on the hard rock fraction class have been determined, as shown in Figure 6. Figure 6 analysis indicates that the bulk density value decreases logarithmically with the increase in the fraction class, while the voidness increases, which is natural. The bulk density and voidness values of the hard rock mixture of 0...100 mm have been determined, which are 1.63 tons/m^3 and 43.8%.

Based on Figure 6 data, it can be seen that the 0...100 mm mixture is close to the minimum fraction of 0...5 mm in terms of bulk density and voidness. Consequently, there is no need to select a specific granulometric composition of hard rocks as a backfill material, since the granulometric composition of the rock mixture formed after the blast corresponds to the minimum voidness values.

Based on the results of laboratory tests to determine the strain characteristics of 0...100 mm rock mixture, a stress-strain curve has been plotted, as shown in Figure 7.

Figure 7 analysis shows that the value of relative hard rock strain naturally changes according to a logarithmic dependence with an increase in the acting stress with a high approximation coefficient, which is typical for rock backfill materials. Thus, under the action of compressive stresses on a rock mixture in the range of 0...7 MPa, the mass strain reaches about 16%. By the nature of the curve, there are three stages of strain during compression. In the range of 0...1 MPa, elastic strain is characteristic, when the rock is easily compressed by removing voids and weak adhesion between particles. Elastic-plastic strain is typical for the range of 1...4 MPa, when strain stabilization is observed, since most of the voids have already been eliminated, and the rocks create resistance to further compression. Plastic strain occurs at compressive stresses above 4 MPa, where further shape changes are caused by rock structure destruction, particle removal and irreversible strains. For numerical modelling of backfill mass subsidence, it is expedient to take the value of the strain modulus in the transition zone from elastic-plastic to plastic strain, since the

Table 3. Physical and mechanical properties of the rock mass and loose rock backfilling

Model element	Density, tons/m^3	Strain modulus, MPa	Internal friction angle, deg	Adhesion, MPa	Tensile strength, MPa
Rock mass (hornblende)	3.34	89000	40	37	13
Rock backfilling	According to laboratory tests			0.02	0

Table 4. Physical and mechanical properties of the paste backfilling

Model element	Density, tons/m^3	Compressive strength, MPa	Tensile strength, MPa	Strain modulus, MPa	Poisson's ratio
Paste backfilling	2.0	3.0	0.21	700	0.28

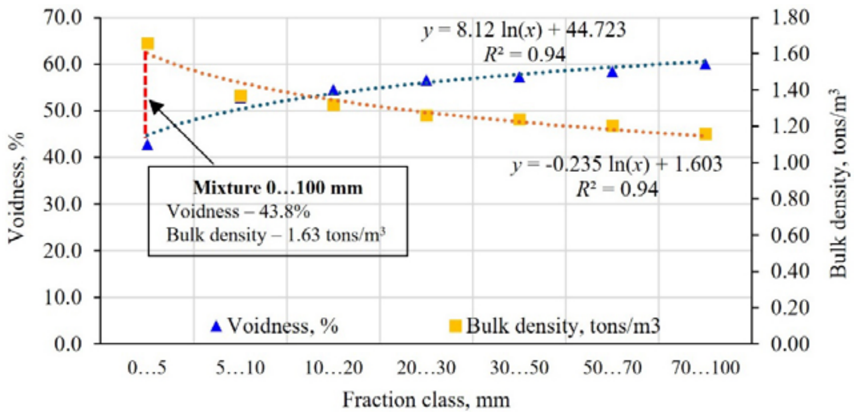


Fig. 6. Dependences of changes in bulk density and voidness by rock size classes

mass self-compaction under the influence of its own weight occurs during the first and second stages of strain. With $\varepsilon = 0.14$ and $\sigma = 4.5$ MPa, the hard rock strain modulus is 32 MPa.

Using a special metal cone, the natural slope angle of the filled-up mass of the studied rock mixture was determined to be 38°. It is known that for loose materials, the natural slope angle is close to the value of the internal friction angle. The internal friction angle of hard rocks in a dump is 35-37°, therefore the values of the 0...1000 mm fractions in the dump and the studied 0...100 mm fraction are close. This indicates the similarity of the mechanical characteristics of the studied fraction and real rocks in the dump, despite the scaling, since the proportionality of the fractions is preserved, and the shapes of the rock particles are similar to full-scale ones. The determined strain modulus also reflects the similar strain processes of the scaled and real fractions. The physical-mechanical properties of rocks are influenced by moisture from atmospheric precipitation, which can be in the range of 5-15%, so it is reasonable to slightly reduce the strain properties and increase the bulk density of rocks (Kovrov, Babiy, Rakishev, & Kuttybayev, 2016). Given the above, the following characteristics are specified in the numerical model for studying the stability and subsidence of the loose mass surface: strain modulus is 30 MPa, internal friction angle of rocks is 35°, bulk density of the mass is 1.85 tons/m^3.

The numerical model of the stability of a loose rock backfill mass of a quarry cavity has been developed, which is modelled under close to dry conditions with low moisture content. Figures 8a and 8b show the resulting displacement and strain curves of the loose rock backfill mass.

Figure 8a shows the development of displacement values in the backfill mass. The displacement curve shows the maximum vertical displacements (subsidence) of the backfill material (dump waste rock) in a filled quarry under the influence of its own weight. Since the scientific interest is in the backfill mass subsidence, the displacements of its surface are assessed

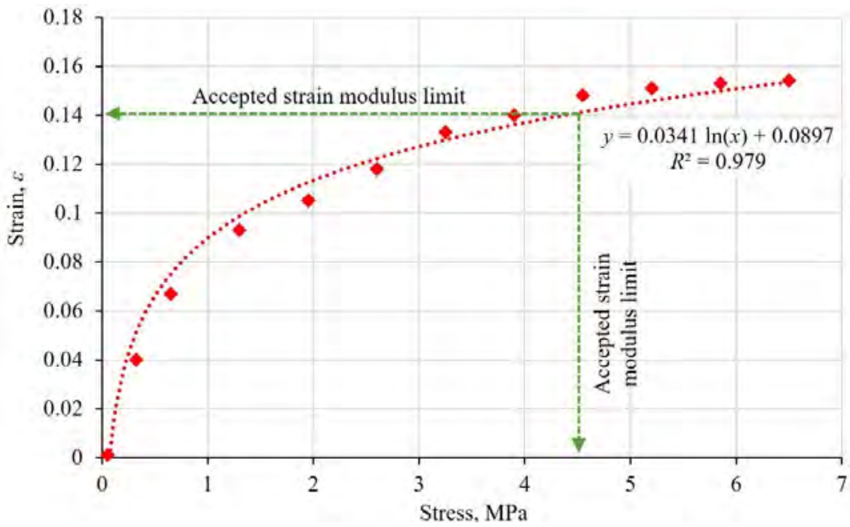


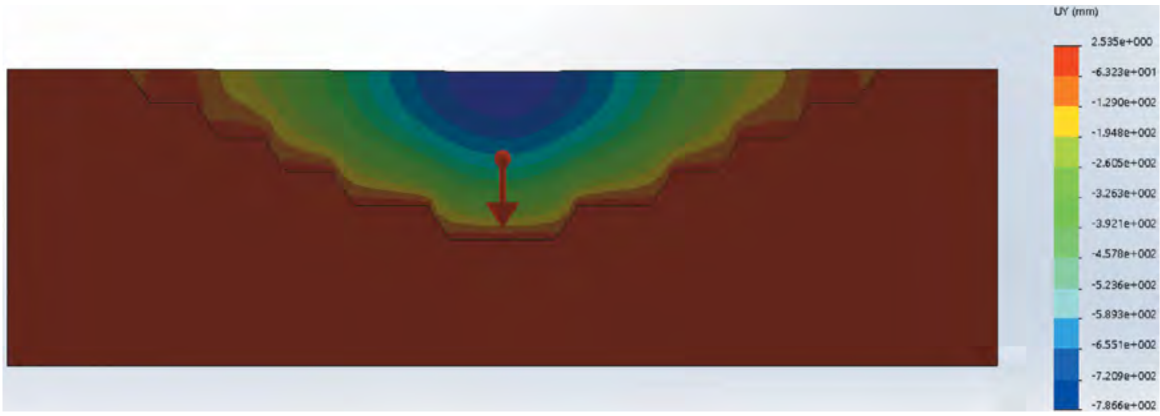
Fig. 7. Stress-strain curve of 0...100 mm hard rock mixture

directly. Thus, due to the quarry cavity geometry, the maximum mass surface subsidence value naturally occurs in the centre of the backfilled quarry, reaching a value of 790 mm. From the centre to the outer walls of the quarry, the displacements also naturally decrease, as the presence of benches reduces the depth and, consequently, the impact of gravity from the filled-up mass weight.

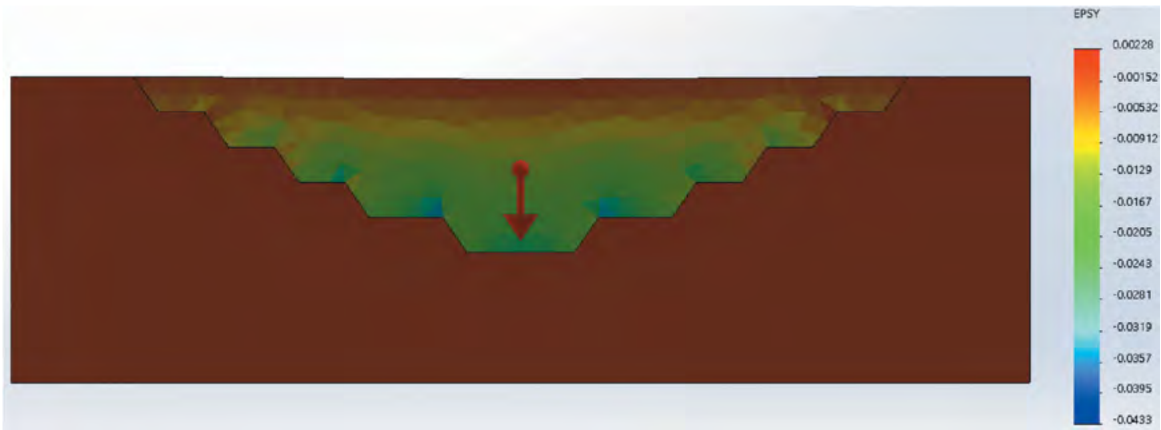
Given the subsidence values and high construction requirements for the bases and foundations of buildings and structures, it is quite risky to build infrastructure facilities on the loose rock mass surface. In addition, the strain properties of loose backfill material can increase under the influence of water saturation, and the resulting subsidence can be even greater. The results presented here illustrate the subsidence of the mass surface with a moisture content of 5-10%.

The strain curve shown in Figure 8b illustrates the distribution of axial rock backfill mass strains in a filled quarry under the action of gravity. The curve shows how the size and shape of the backfill material changes in different parts of the quarry due to compaction under its own weight. The central part of the quarry (blue and green areas) shows the greatest compressive strains, indicating a significant compaction of the material in these areas. The maximum strain values reach about 0.03...0.043 (relative strains), which indicates a significant compression. Smaller strains are observed in the upper part of the quarry and closer to the edges (green and yellow colors). This is due to the fact that these zones are closer to the surface and are less exposed to the pressure of the overlying layers.

Next, the results of numerical modelling of an alternative method for forming a backfill mass based on cemented paste backfilling, which, unlike a loose mass, is monolithic, are presented (Figs. 9a and 9b). In the model of paste backfilling, its mechanical characteristics are reduced taking into account water saturation, since it has been proven that at 10% water saturation of the mass, its strain modulus decreases by 20% (Wang & Fu, 2021; Wang, He, & Yang, 2023). Figure 9a analysis shows that the values of the backfill mass surface subsidence during paste backfilling are an order of magnitude different from loose rock backfilling. Thus, the maximum subsidence value is also observed on the backfill mass surface in the centre of the quarry and reaches 43 mm, compared to 715 mm for loose rock backfilling. Surface subsidence also naturally varies from the quarry centre

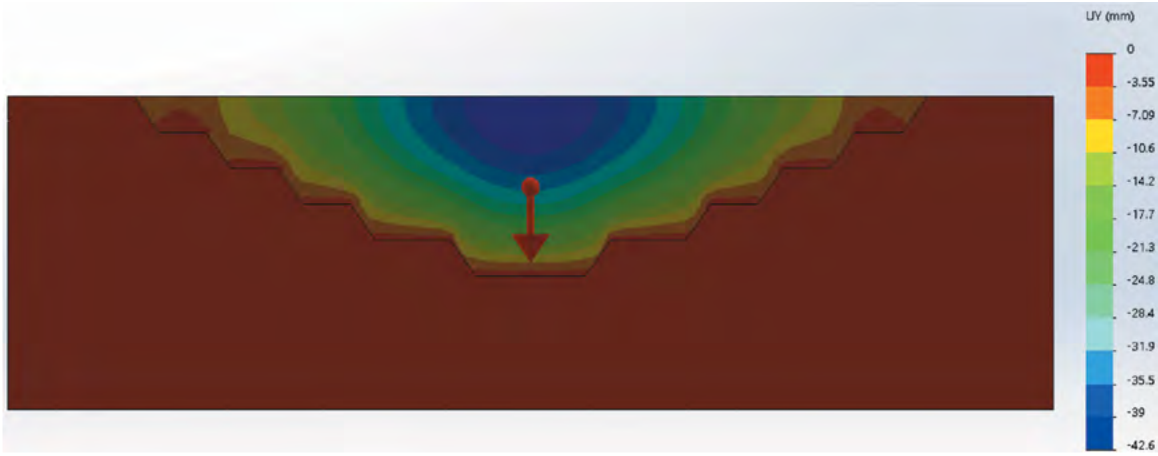


(a)

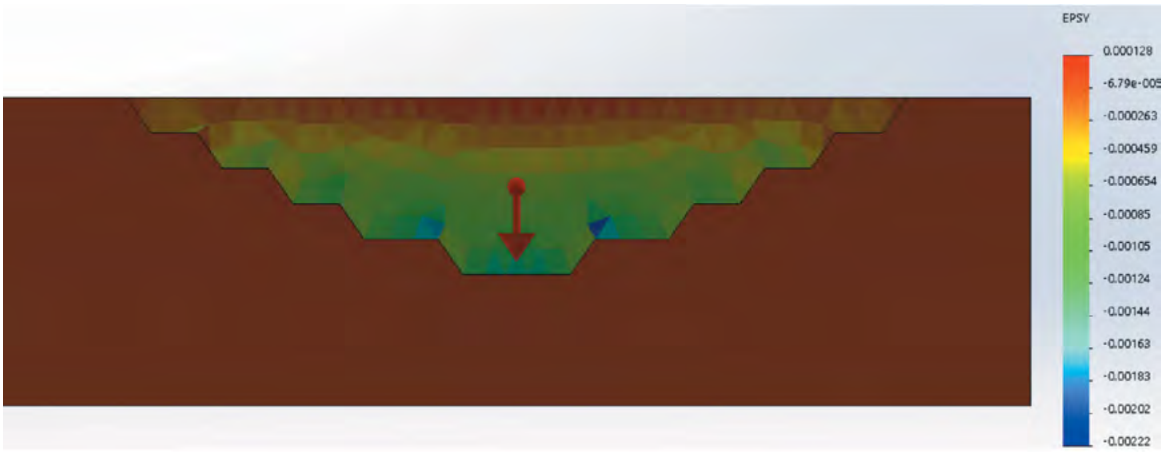


(b)

Fig. 8. Results of numerical modelling of rock backfilling: (a) displacement curve along *Y-axis*; (b) strain curve along *Y-axis*



(a)



(b)

Fig. 9. Numerical modelling results of cemented paste backfilling: (a) displacement curve along *Y-axis*; (b) strain curve along *Y-axis*

to edges. The difference in the subsidence values is due to significant difference in physical-mechanical properties, namely the strain modulus, adhesion and internal friction angle. After hardening and gradually gaining strength, the backfill mass behaves like a monolith, resisting compression and shear under the action of gravity.

It is quite clear that the surface subsidence value directly depends on the specific physical-mechanical characteristics of the backfill mass, which, in turn, are determined by the properties of the source components and their proportions. The research performed is aimed at demonstrating a conditional difference in the behaviour of loose and paste masses based on specific physical-mechanical properties, which allows us to see the differences in their strain characteristics.

By monitoring points No. 1 – No. 5 (Fig. 5), the displacement value is measured along the width of the backfill mass surface with different methods of its formation, and the results are graphically presented in Fig. 10. Graph analysis (Fig. 10) demonstrates the situation with the development of strains on the backfill mass surface in the quarry, which are maximum in the centre and decrease towards its edges, due to the impact of the gravity component. The results obtained are important for understanding the geomechanical state of different backfill mass types, predicting its subsidence and assessing stability during the possible construction of various facilities on the restored earth's surface in the mined-out quarry space.

Discussion

In conditions when in the Kryvyi Rih region, only traditional filling with dump waste rocks is used to reclaim technologically disturbed lands, an alternative method such as cemented paste backfilling may be quite promising and effective. The most important advantage is that the region has significant reserves of iron ore beneficiation tailings, some of which are in close proximity to inactive quarries and mine failure zones (Petlovanyi et al., 2023b). On the one hand, the

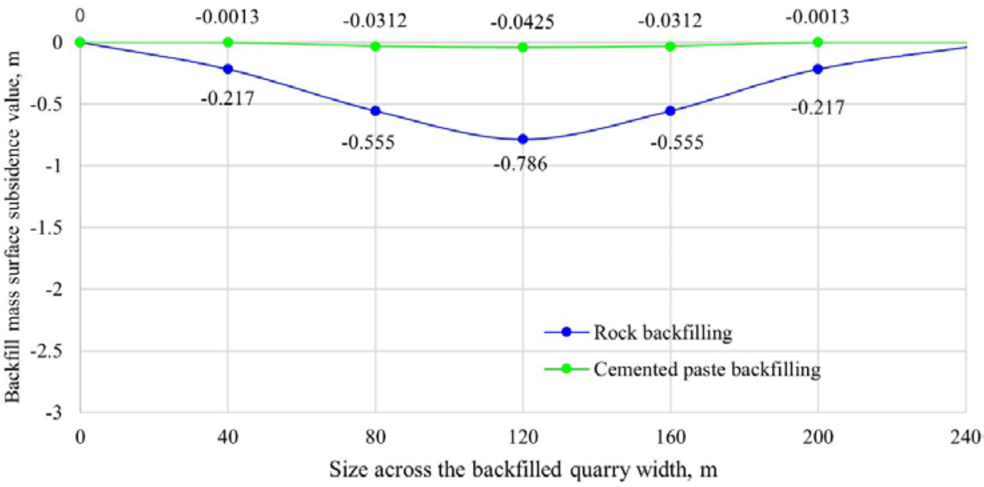


Fig. 10. Development of the maximum backfill mass surface subsidence across the quarry width at different methods of its formation

transition to a monolithic mass state increases economic costs, but on the other hand, it is strategically important for improving the environmental situation, developing infrastructure projects and the region's economy in the future, as this method is more expedient given the set of considered factors. Mining enterprises spend substantial investment funds on the construction of new dumps and tailings storage facilities. An example is the construction of a new 500-hectare tailings dump in the region with an investment volume of $150 million. Such funds can be used to develop alternative backfill technologies.

A limited number of scientific studies are devoted to the use of methods alternative to loose rock backfilling in open technogenic cavities. Thus, Zhang et al. (2021) studied only the impact of paste backfilling in a quarry on underground mining operations under the quarry. A paper (Chen, Niu, & Xiao, 2023) examines the influence of moisture from paste backfilling in a quarry on the stability of its walls. Studies have also been conducted on the influence of paste backfilling on slope stability and aquifer contamination (Chen et al., 2022). Physical-mechanical properties of cemented rock backfilling were studied to fill one of the quarries in Canada (Shrestha et al., 2008). Consequently, monolithic technologies for backfilling quarry cavities are given some attention by the scientific community, but the study of geomechanical stability of the mass and its surface requires further comprehensive research.

In our research, we compare the conditional stability of different types of backfill masses in the mined-out space of a quarry when forming loose rock and cemented paste backfill. Physical-mechanical properties of a hard rock mixture simulating a backfill material for filling a quarry were tested in laboratory conditions. A number of scientists have obtained similar results in terms of physical content of the strain properties of loose rock fractions (Li, Zhang, & Gao, 2016; Zhang et al., 2019; Meng et al., 2019), but this is mainly coal mine rock and scientific studies of hard rock as a backfill material are rare. The obtained results of bulk density, voidness and strain characteristics of the hard rock mixture make a certain contribution to the understanding of hard rock strain processes. Studies have shown that a mixture of rocks of 0...100 mm, which simulates the fractional composition of full-scale dump waste rocks of 0...1000 m in terms of voidness and bulk density, is close to finely dispersed fractions and is optimal for use as a backfill material. The similarity of mechanical processes of laboratory and full-scale mixtures of hard rock fractions has been substantiated. The studied properties formed the basis of a numerical model for the rock backfill mass stability in the quarry cavity. The results obtained can be compared with the close results of field studies of the maximum subsidence of the filled-up rock mass in a 260 m deep quarry, which are 4.0 m (Williams, 2000).

To form a paste backfill mass, a mass is tested, which will reach a constant strength of 3.0 MPa during the period of backfilling the quarry cavity. It is believed that, given the wide mineral and raw material base of cementitious materials, it is quite possible to create a backfill mass of the specified strength.

To do this, the mechanical parameters from well-known scientific papers were studied, which are estimated to be possessed by the mass at the specified compressive strength. The results of numerical modelling indicate that the monolithic mass in terms of surface stability in the studied quarry cavity significantly predominates the loose rock mass. The obtained results of the surface subsidence indicate that the final strength value of paste backfilling of 3.0 MPa is sufficient to form a stable surface of the monolithic backfill mass and it makes no sense to increase the strength or the dosage of the cementitious material, which will lead to an increase in the cost of backfilling operations. In addition, the formation of paste backfilling in a quarry cavity opens up a wide range of possibilities for using the restored earth's surface.

However, it is impossible not to take into account that the formation of the backfill mass in open quarry cavities will be influenced by climate conditions. The paste backfill is supposed to be delivered to a quarry by pipeline transport, and the subsequent hardening and formation of the paste backfill mass is influenced by the ambient temperature, which, together with the intensity of precipitation, will have a significant impact on the quality of the mass and the organization of backfilling operations. A number of researchers have studied the effect of temperature on the hardening of paste backfill mixtures (Han, Zhang, & Sun, 2019; Xu, Zhang, & Liu, 2020; Wang et al., 2023), indicating an increase in the setting time and a decrease in their strength properties. Based on the generalization of researches and taking into account dynamics of change in average monthly temperatures and precipitation intensity in the city of Kryvyi Rih over the past three years, we believe that the rational period for using paste backfilling for open technogenic cavities is from April to October (Fig. 11.)

The influence of atmospheric precipitation during the expedient period of paste backfilling can be solved by the specific organization of backfilling operations and scientific research on regulation of paste backfilling properties.

Therefore, in order not to lose the rate of filling the quarry cavity and, accordingly, the rate of the earth's surface restoration, it is proposed in the period of unfavorable climate conditions for paste backfilling (from November to March) to form a rock backfill mass, the condition of which does not depend on climate conditions. This approach is illustrated in Figure 12.

As can be seen from Figure 12, the backfill mass has a layer-type structure, where the rock and paste backfill layers have different mechanical parameters, which can lead to surface subsidence, that differ from those obtained in this study. Assessment of the combined backfill mass subsidence should become the direction of further scientific research. It is necessary to assess from a geomechanical point of view how the surface subsidence will change with differ-

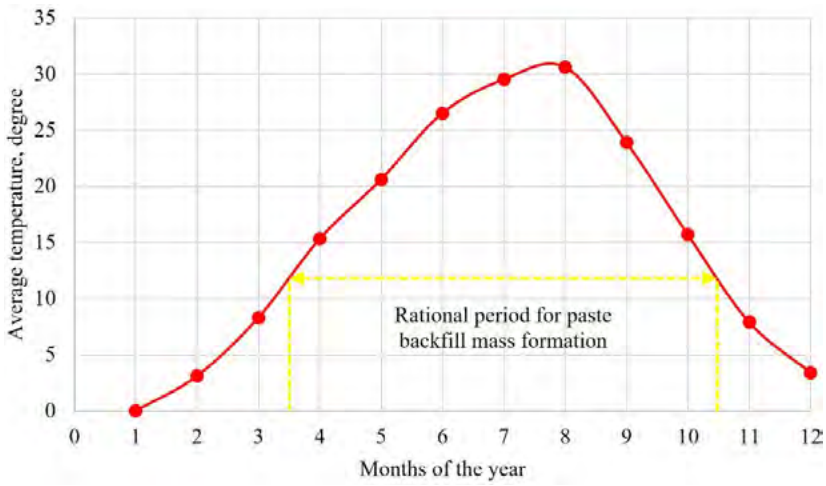


Fig. 11. Dynamics of change in average monthly temperatures in the city of Kryvyi Rih

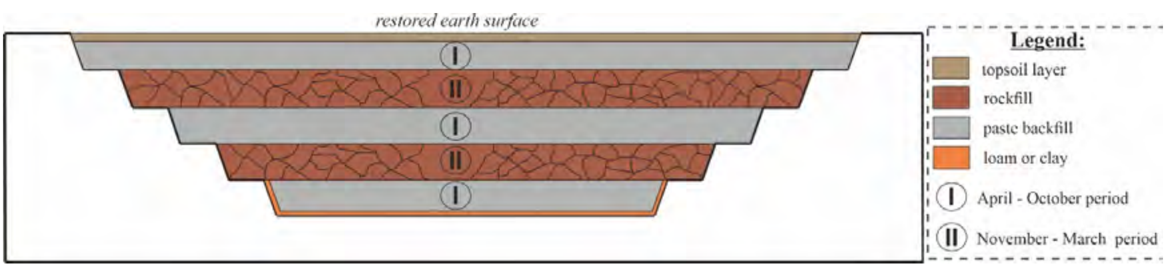


Fig. 12. Combined backfill mass structure for filling mined-out quarry spaces

ent options of the correlation of the backfill layers, such as: thickness of the rock and paste layers is the same; the thickness of the rock layer is greater than the paste layer and vice versa. That is, it is necessary to determine the best geomechanical situation for the correlation of layers of different backfill types, taking into account their mechanical properties. For assessment, the dependence of the surface subsidence value on the total equivalent strain modulus of the mass can be determined, which takes into account the strain modulus, density and height of each layer in the system.

Conclusions

In the presented research, the properties of loose rock backfill mass and paste backfill mass have been studied as an alternative option for filling inactive quarry cavities in the Kryvyi Rih region based on laboratory tests and analysis of the achieved properties. The stability of different types of backfill masses has been assessed, their comparison has been provided, as well as the expediency and peculiarities of using cemented paste backfilling have been discussed.

1. A vector for improving the directions of backfilling the mined-out spaces of quarries and mine failure zones in the Kryvyi Rih region has been formed, which consists in the transformation of the physical state of the backfill mass from loose to monolithic, which is explained by achieving the necessary geomechanical stability of the restored surface for its reasonable use in the economic potential of the region. Taking into account the significant volumes of accumulated beneficiation tailings in the region and the limited ways of their utilization, it is recommended to use them as part of cemented paste backfill, which will lead to an improvement in the environmental situation. The strengths and weaknesses of comparable backfill mass types have been analysed.

2. A laboratory research methodology has been developed to determine the backfill material properties and numerical modelling of the stability of various types of backfill masses on the example of a specifically chosen quarry. The basic physical-mechanical characteristics, such as bulk density, voidness, internal friction angle of rock fractions and rock mixtures of 0...100 mm as backfill material corresponding to the rocks in the dump have been studied. In addition, logarithmic dependences of the pattern of their change on the granulometric composition have been determined. It has been found that the rock mixture of 0...100 mm in terms of bulk density and voidness is close to minimum fraction of 0...5 mm, which does not require the need to select a certain fractional composition. The dump waste rock fractional composition has better properties.

3. The strain characteristics of a 0...100 mm rock mixture have been studied and a stress-strain curves have been plotted, which have a logarithmic relationship and are characterised by three stages of strain: elastic, elastic-plastic, and plastic. The strain modulus value in the zone of transition from elastic-plastic to plastic strains has been determined, which is used in numerical modelling. The similarity of the mechanical characteristics of the studied mixture of 0...100 mm to the full-scale characteristics of dump hard rocks has been substantiated. Based on the studied experience of achieving the mechanical characteristics of paste backfilling, their initial data for numerical modelling have been compiled.

4. The results of numerical modelling of the stability of the backfill masses show that the maximum backfill mass surface strains are observed in the centre and gradually decrease towards the quarry edges. In the case of rock backfilling, the maximum strains reach 780 mm, while calculations of paste backfilling show a significant decrease in the subsidence value, reaching only 43 mm. The difference in subsidence values is due to a significant difference in physical-mechanical properties, namely the strain modulus, adhesion and internal friction angle. After hardening and gradually gaining strength, the paste backfill mass behaves like a monolith, resisting compression and shear under the action of gravity.

5. It is noted that the formation of a paste backfill mass in open quarry cavities is influenced by climate conditions, namely, ambient temperature. Based on the study of average monthly temperatures and hardening conditions of paste backfill mixtures, as well as taking into account the need to maintain intensive reclamation operations, a seasonal approach and the formation of a combined backfill mass are proposed: in the period from April to October to form a paste backfill mass, in the period from November to March to form a rock backfill mass.

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