NATURAL RESOURCE MANAGEMENT AND ENVIRONMENTAL PROTECTION IN MINING AND PROCESSING OF MINERALS

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Abstract. The article presents the main scientific and practical results during the creation of prerequisites for solving regional environmental challenges for balanced resource conservation during the extraction and processing of mineral resources. In particular, the properties of materials were investigated during the activation of industrial waste, such as binder (granulated blast furnace slag), inert aggregates (a product of the rumbling of substandard materials) and mixing water (mine water) during the manufacture and transportation of hardening mixtures to the place of their stacking. Technologies and technical means for transporting hardening backfill mixtures have been studied and an algorithm has been developed for calculating schemes for their pipeline transport into underground developed spaces containing 0.10-0.35 dispersed particles with a concentration of solid particles in water of 0.10-0.85 and a standard cone settlement of 10-13 cm. It has been proven that the optimal coarseness of waste, taking into account grinding, transportation and stacking of mixtures in man-made cavities, is in the range of 25–35 mm. At the same time, the optimal fineness of grinding additives to the binder is 50-60% of particles with a size of 0.074 mm. With the same amount of binder, the strength of the control samples, in which the fineness of grinding the additive was 88% of the coarseness class – 0.074 mm, is 5 times greater than the fineness of 50%. The application of methods of activation of the components of the hardening mixture increases their activity as a whole by 10-40%. The use of beneficiation waste processed in disintegrators increases the strength of the embedded massif by 25-30% or reduces the consumption of cement by 40-50% while maintaining the required strength characteristics. The use of beneficiation wastes as an inert aggregate in the foundation mixture allows them to be disposed of, which leads to a reduction in laying costs, a reduction in cost, environmental safety and labor protection, and mineral resources during ore mining and beneficiation. It is recommended to continue research and provide funds (at the expense of enterprises, local and central authorities) to minimize the negative effects on human health from exposure to heavy metals and environmental protection, taking into account the peculiarities of their combined impact on the population and workers of the mining and metallurgical industry.The so far rare experience of strengthening the radiation and social protection of the population of Zhovti Vody, Ukraine, which has been forced to live for more than 70 years in the zone of influence of uranium industry facilities, is presented.

Keywords: mineral resources, extraction and processing, separation and activation, ecology and resource conservation, efficiency

УПРАВЛЕНИЕ НА ПРИРОДНИТЕ РЕСУРСИ И ОПАЗВАНЕ НА ОКОЛНАТА СРЕДА ПРИ ДОБИВА И ПРЕРАБОТКАТА НА ПОЛЕЗНИ ИЗКОПАЕМИ

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РЕЗЮМЕ: Статията представя основните научни и практически резултати при създаването на предпоставки за решаване на регионалните екологични предизвикателства за балансирано опазване на ресурсите при добива и преработката на полезни изкопаеми. Свойствата на материали по време на активацията на промишлени отпадъци, като например свързващо вещество (гранулирана шлака от доменни пещи), инертни пълнители (продукт от пресяването на нестандартни материали) и вода за смесване (руднична вода) са изследвани в хода на производството и транспортирането на втвърдяващите се смеси до мястото на насипването им. Изследвани са технологиите и техническите средства за транспортиране на втвърдяващи се засипни смеси и е разработен алгоритъм за изчисляване на схеми за транспортирането им по тръбопровод в подземни изкопи, съдържащи 0,10-0,35 дисперсни частици с концентрация на твърди частици във вода 0,10-0,85 и стандартно конусно слягане от 10-13 cm. Доказва се, че оптималният размер на едра зърнистост на отпадъците, при отчитане на смилането, транспортирането и насипването на втвърдяващите се смеси в изкуствени кухини, е в диапазона 25–35 mm. В същото време оптималната ситност на частиците на добавките към свързващото вещество е 50-60% от частиците с размер 0,074 mm. При същото количество свързващо вещество, якостта на контролните проби, при които ситността на частиците на добавката е 88% от класа на едрата зърнистост– 0,074 mm, е 5 пъти по-голяма от фиността на частиците от 50%. Прилагането на методи за активация на компонентите на втвърдяващата смес повишава тяхната активност като цяло с 10-40%. Използването на отпадъци от обогатяването, обработени в дезинтегратори, увеличава якостта на масата на запълване с 25-30% или намалява разхода на цимент с 40-50%, като същевременно запазва необходимите якостни характеристики. Използването на отпадъци от обогатяването като инертни пълнители във втвърдяващата смес позволява тяхната утилизация, което води до намаляване на разходите за запълване, по-ниска себестойност, екологична безопасност и охрана на труда при добива и обогатяването на минерални суровини. Препоръчва се научните изследвания да продължат и да се осигурят средства (за сметка на предприятията, местните и централната власт) за опазване на околната среда и за минимизиране на негативните последици върху човешкото здраве от излагане на тежки метали и, като се вземат предвид особеностите на тяхното комбинирано въздействие върху населението и работниците от минната и металургичната промишленост. Представен е и засега не дотам богатият опит за засилване на радиационната и социалната защита на населението на Жолтие Води, Украйна, което е принудено да живее повече от 70 години в зоната на въздействие от обекти на урановата промишленост.

Ключови думи: минерални ресурси, добив и преработка, сепариране и активиране, екология и опазване на ресурсите, ефективност

Introduction

Currently, in developed mining countries of the world, 5-8% of all produced electricity is spent on mechanical methods of mineral processing. Approximately 80% of this value is energy consumption for grinding. The main operation associated with the preparation of waste from mining and metallurgical production for use as a hardening mixture for filling the mined-out space of mines is grinding and activation (Aben et al., 2019, Antonelli et al., 2020).

Therefore, increasing the efficiency of activation of the components of the hardening filling mixture using waste from mining and metallurgical production by grinding them and reparing them at filling complexes, as well as transporting them to the place of their placement, ensuring a reduction in the energy intensity of the technological process for preparing the hardening mixture and increasing environmental safety is an urgent task that requires urgent solutions (Beiyuan et al., 2017, Basarir et al., 2018).

Vibro-gravity transport installations deliver hardening mixtures to a distance significantly exceeding the height of the vertical stack. At the Wismut mine (Germany), the hardening mixture with the Budtsnilu cone slump of 8.0 cm was fed to a distance 3 times greater than the height of the vertical line of the filling pipeline.

The works of domestic and foreign scientists formulated the global problem of the accumulation of mining waste due to the lagging behind the possibilities of processing mineral raw materials from the possibilities of their mining (Chernov et al., 2001, Chetveryk et al., 2017).

This problem is characterised by the accumulation of processing tailings on the earth's surface and the alienation of significant areas of fertile land from secondary products. Scientific and practical results were obtained by the research on the development of hardening mixtures with reduced consumption of binder for laying the produced space of chambers and technology and recipes of hardening mixtures from tailings for filling maps of surface storage facilities (Franchuk et al.,2000, Dereviahina et al., 2019). The problem of searching for alternative and complex binders and inert aggregates based on non-traditional production waste is an important scientific, practical, and social task that requires an urgent solution.

This work is a continuation of research, the main scientific and practical results of which are most fully presented in the works with the participation of the authors (Radiation et al., 2015, Onika et al., 2020).

*Research Object.*The object of the research is technologies and technical means for the extraction and processing of mineral resources by recycling mining and metallurgical waste into underground mined-out spaces as components of hardening backfill mixtures, taking into account the technological processes of activating the binder and substandard inert filler during their manufacture and transportation to the place of placement.

Purpose of the study. The objective of the research is to create prerequisites for solving regional environmental challenges for balanced resource conservation during the extraction and processing of mineral resources. This will allow us to justify technologies and technical means for recycling mining and metallurgical waste into underground mined-out spaces as components of hardening backfill mixtures, taking into account the technological processes of activating the binder and substandard inert filler during their manufacture and transportation to the location of their placement.

The following tasks were set and solved for the study:

1. To perform mathematical and physical modeling, as well as to calculate the parameters of vibratory gravity transport of hardening backfill mixtures.
2. To recommend vibratory transport units to increase the activity of solid components (binder and inert filler) of the hardening backfill mixture.
3. To offer a new set of technical means for activating the binder (granulated blast furnace slag), inert fillers (screening product of substandard materials), and mixing water during the production and transportation of hardening backfill mixtures.
4. To show promising research for conducting scientific substantiation and development of preventive measures to minimise negative consequences on human health and the environment in the zone of influence of the mining and metallurgical industry.

Research methods. The analysis of literary sources, methods of theoretical research and generalisations was performed using the study of dynamics (in the resonance zone, the Volterra principle and the concept of the complex modulus of elasticity introduced by E. S. Sorokin were used), mathematical statistics, physical and mathematical modelling, calculations, laboratory and full-scale experimental studies, industrial tests in the conditions of operating enterprises using standard and new methods with the participation of the authors, by special programs, such as GIS K-MINE®, VENTSIM, etc. Their implementation, in particular with the help of GIS K-MINE®, showed positive results and contributes to the solution of applied issues during the development of reserves of mineral deposits (Rudko G.I., Netskiy O.V., et al., 2018). Dependencies were obtained on the basis of analytical, experimental studies and experience in the operation of installations for pipeline transport of hardening mixtures to mines (Rudko G.I., Lovinyukov V.I. 2015).

Theory of the issue. *Determination of the parameters of the horizontal section of the pipeline vibration gravity transport of hardening mixtures.* The pipeline is subjected to vibration action of alternating force, which reduces the resistance to transportation. The main parameters of the vibration delivery are: the length of transportation (*L*), the height of the vertical pipeline (*H*), the length of the sections (l_1) and the location of the vibration exciter within the section (l_2) (Figure 1).

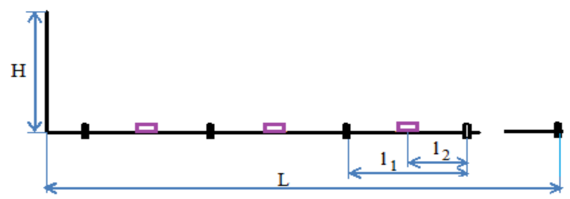

Fig. 1. Installation diagram of vibratory gravity transport (other designations in the text)

The effect of vibration ensures thixotropic liquefaction of the dispersed medium and movement of particles of the mixture in contact with the walls of the pipeline. The effect of vibration on the hardening backfill mixture is manifested by the acceleration of pipeline oscillations, which is characterised by the coefficient of the vibration transport mode

$$\Gamma = \frac{A \cdot \omega^2}{g} \quad , \qquad (1)$$

where *A* and *ω* are the amplitude and frequency of oscillations, respectively, Hz and s^{-1} and *g* is the acceleration of gravity, m/s^2.

At *Γ*=0.6…1, a thixotropically liquefied wall layer is created and stratification of the hardening mixture is excluded (for a mixture located in a container with a free surface, for a pipeline, the value of *Г* can be chosen somewhat larger). Focusing on the value of *Г* from expression (1), specifying the value of *A,* the frequency of forced vibrations ω is found (for inertial vibration exciters with an asynchronous drive or motor-vibrators, ω is usually selected and the amplitude *A* is determined). Effective vibration impact on the mixture is ensured by oscillating the pipeline with a minimum value of the vibration transport mode coefficient

$$\Gamma_{min} = \frac{\rho_r - \rho_o}{\rho_r}, \qquad (2)$$

where ρ_r, ρ_o are the densities of the aggregate particles and the dispersed medium, respectively, kg/m^3.

Calculation of the process parameters of the pipeline. The peculiarity of the movement of the hardening backfill mixture in the vibration gravity transport units is the presence of the main flow, in which the viscous-plastic properties of the mixture are preserved, and the near-wall layer, which is characterised by low viscosity. The stratification of the mixture is excluded at the speed of its longitudinal movement of 0.5-0.7 m/s - for mixtures with aggregate of up to 5.0 mm in size and 0.7-1.0 m/s - for mixtures with aggregate of 5.0-40.0 mm in size. The internal diameter of the pipeline (minimum) is determined from the expression:

$$D_m = 24{,}45 \cdot V_{\text{ср}} \cdot d_{\text{ср}} \cdot \sqrt{\frac{\rho}{\tau_o}}, \qquad (3)$$

where $V_{\text{ср}}$ is the average transportation speed, m/s; $d_{\text{ср}}$ is the average size of the transported material, mm; *ρ* is the density of the filling mixture, kg/m^3; τ_o is the ultimate shear stress of the mixture, Pa.

The pipeline capacity (the unit's capacity, m^3/s) is determined from the expression:

$$Q = V\frac{\pi \cdot D^2}{4}, \qquad (4)$$

where *D* is the internal diameter of the pipeline, m; *V* is the speed of movement of the mixture, m/s.

The most effective vibration effect on the hardening mixture occurs at a speed of its movement V=1.0…1.5 m/s. Then the pipeline diameter is specified according to the expression is specified according to the expression:

$$D = 2 \cdot \sqrt{\frac{Q}{\pi \cdot V}} \geq 24{,}45 \cdot V \cdot d_{\text{ср}} \cdot \sqrt{\frac{\rho}{\tau_o}}. \qquad (5)$$

The specific pressure loss in the horizontal section of the pipeline is determined from the expression:

$$\Delta p = \frac{\frac{158{,}73}{D^3} + \frac{4\tau_0'}{D \cdot \eta_1}}{\frac{6}{\eta} + \frac{1}{\eta_1}}, \text{ Pa/m} \qquad (6)$$

where τ_0' is the shear stress of the wall layer, Pa; $\eta = 0{,}1 \cdot \sqrt{\tau_o}$ is the viscosity of the filling mixture, Pa/s; $\eta_1 = 0{,}1 \cdot \sqrt{\tau_0'}$, is the is the viscosity of the thixotropically liquefied wall layer, Pa*s:

The maximum range of supply of the hardening mixture by the installation is determined from the expression:

$$L = \frac{p_c}{\Delta p}. \qquad (7)$$

Dynamic parameters of the pipeline section. To ensure effective vibration impact on the hardening backfill mixture, it is necessary to provide the horizontal section of the pipeline in the transverse direction with vibration parameters that ensure the required vibration displacement coefficient. For this purpose, the horizontal pipeline section is divided into a number of sections driven by a separate vibration exciter. The length of the pipeline section l, serviced by one locally installed vibration exciter, is selected in such a manner that the transverse vibrations of the pipe along its entire length are within the limits of Г=0.6…1.0. Each section is installed on a number of elastic supports; under the influence of the vibration exciter, the pipe with the filler (hardening mixture) performs bending vibrations in the horizontal and vertical planes. The calculation scheme of the section is shown in Figure 2.

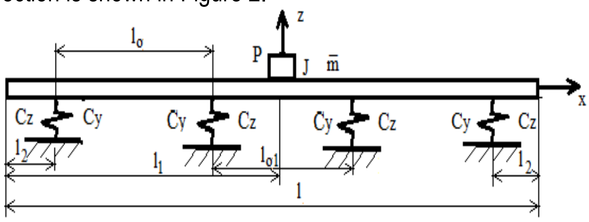

Fig.2. Scheme for determining bending vibrations of a horizontal pipeline section: *l* is the transportation length, m; *l*$_o$, *l*$_1$, *l*$_2$ are the distance between the vibration exciter supports, the length of the sections between the vibration exciters, and the length to the vibration exciter location within the section, respectively, m; $\bar{m}$ is the distributed mass of the section, kg/m; *P* is the disturbing force of the motor-vibrator, *N; J* is the moment of inertia of the section section, m^4; *x, z* are the horizontal and vertical coordinates of the section, respectively, m; *Cz, Cy,* are the rigidity of the elastic support along axes z and y, respectively, N/m.

When the vibration exciter is located in the center, the section oscillations will be symmetrical, and only oscillations with odd harmonics will be excited. The general picture of oscillations of a section of sufficiently long length (when its bending oscillations appear) taking into account seven harmonics is shown in Figure 3.

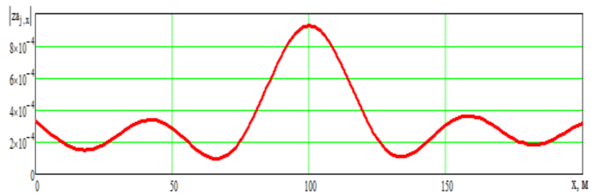

Fig. 3. Bending the pipe along the length of the section

As follows from the graph, in the steady state, the greatest amplitude of deviation occurs in the middle of the pipe, and the amplitude of oscillations decreases towards the periphery.

Calculation of elastic support parameters. The total rigidity of the support shock absorbers is determined based on the gravity of the pipeline with the process load. Gravity of the pipeline:

$$P_{\text{тр}} = g \cdot (l \cdot \bar{m} + m_{\text{в}}), \qquad (8)$$

where l is the transportation length, m; $m_{\text{в}}$ is the is the motor-vibrator mass motor-vibrator mass, N; $\bar{m}$ is the distributed mass of the section, N, which is determined from the expression:

$$\bar{m} = \rho_{\text{м}}\frac{\pi \cdot (D^2 - d^2)}{4} + \rho_c\frac{\pi \cdot d^2}{4}, \text{kg/m}, \qquad (9)$$

$\rho_м, \rho_c$– respectively, the density of the pipe material and the hardening filler, kg/m^3; E – the modulus of elasticity of the pipe material, Pa; a – “natural velocity of the section”, cm/s:

$$a = \sqrt{\frac{EJ}{\bar{m}}}\text{, m}^2\text{/s. ;} \qquad (10)$$

β – parameter characterising elastic supports:

$$\beta = \sqrt[4]{\frac{Cp}{E\cdot J}}\text{, 1/m.} \qquad (11)$$

Cp – linear rigidity of elastic foundation, equal:

$$Cp = \frac{n\cdot Cz}{l}\ , \qquad (12)$$

Cz – rigidity of elastic support, n – number of supports.

Rigidity of one shock absorber, taking into account their paired arrangement in the support:

$$C_{z1} = 2\cdot n\frac{P_{\text{тр}}}{(1{,}4\div 2)\cdot A(l_1)}. \qquad (13)$$

Considering that it is possible to start the motor-vibrators in the absence of a process load, a higher value of the coefficient should be selected. The height of the elastic element is selected based on the permissible settlement [$\boldsymbol{k_h}$], or on the value of the permissible load [$\boldsymbol{\sigma}$]. Usually (depending on the brand of rubber) [$\boldsymbol{k_h}$] = 0.1 ... 0.2 is selected. Considering the intensity of vibrations and possible heating of the element, we take [$\boldsymbol{k_h}$] = 0.1. As a result, we obtain

$$h = (2{,}4 \div 3)[k_h]\cdot A(l_1). \qquad (14)$$

Massive rubber support elements are made cylindrical with a central ventilation hole. Knowing the elastic modulus for shock-absorbing rubber E_p, the diameter of the elastic element is determined as:

$$(D-d) = \sqrt{\frac{C_{z1}\cdot h}{\pi\cdot E_\text{p}}}. \qquad (15)$$

Next, the dimensions of the elastic elements and the length of the section are adjusted, and it is checked that they do not go beyond the permissible limits.

Materials and methods

The installation of vibration-gravity transport of hardening filling mixtures at the Shokpak-Kamyshovoye ore deposit (Republic of Kazakhstan) included a vertical riser and a horizontal pipeline (Figure 4). The supply of hardening filling mixtures was carried out in portions of up to 400 m^3.

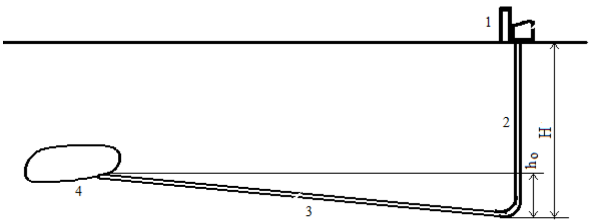

Fig. 4. Scheme of vibration-gravity pipeline transport of hardening mixtures: 1 – filling complex; 2 – well; 3 – cross-cut; 4 – man-made voids; *H* – depth of the filling hole to the earth’s surface, m; h_o – height of rise of hardening mixtures to man-made voids, m

The sectioned section of the pipeline was installed on rubber shock-absorbing supports, and sections of the pipeline 200 m long were equipped with vibration exciters. Under the influence of vibration, the mixture acquired a state of increased fluidity (Paul et al., 2018).

In the problem being solved, along with the required energy intensity, the required granular composition of the final product must be ensured. For example, the optimal size of waste is determined taking into account the costs of crushing, pipeline transport, and the density of their placement in waste chambers should be in the range of 25–35 mm. Thus, the grinding process must also be characterised by grinding efficiency. This parameter is selected as a controlling parameter. At the mines of the State Enterprise "SchidGZK", Ukraine, the most widely used technological schemes for preparing a hardening backfill mixture on surface stationary backfill complexes are based on a binder made from granulated blast furnace slag and low-grade sand (Figure 5).

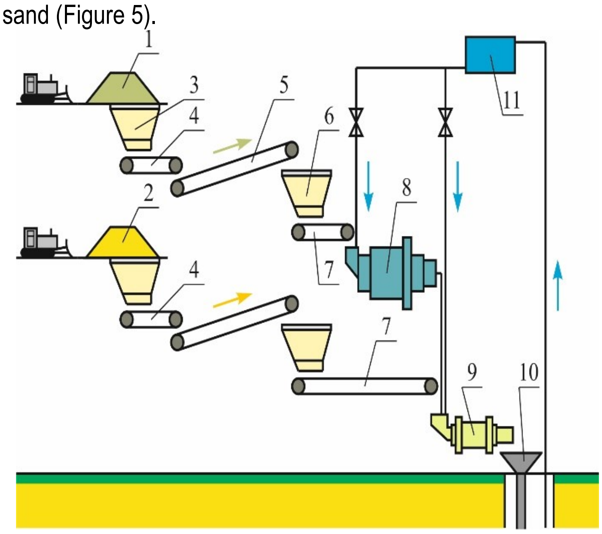

Fig. 5. Technological diagram of the filling complex: 1 – slag; 2 – sand; 3 – receiving bunker; 4 – feeder; 5 – conveyor; 6 – storage hopper; 7 – dispenser; 8 – ball mill; 9 – mixer; 10 – receiving funnel; 11 – container for mixing water

To separate lumps of clay and other impurities, the sand passes through a screening grid installed above the intermediate hopper. After dosing, the slag in a certain ratio with water enters a ball mill, and then in the form of a pulp into a mixer, where it is mixed with sand. Water is also supplied to the mixer to give the filling mixture the required mobility. The finished mixture enters the receiving funnel and is then transported through pipes in a gravity-pneumatic mode into the mined-out space.

At the enterprises of Tselinny Mining and Chemical Combine JSC and TsGKH JSC (Republic of Kazakhstan), vibration, mechanical and lectrochemical activation devices were used to obtain a hardening backfill mixture with a strength of 0.2–1.2 MPa.

Increased activity was achieved through vibration activation of inert materials, mechanical activation of the binder components of the mixture during its transportation, and electrochemical activation of water. The activation efficiency was determined indirectly by the ratio of binders.

Activity equivalent: the amount of activated binder material from waste, equivalent in binder properties to cement, was determined by the rational ratio of binder materials (Poturaev et al. 1989). Mechanical activation of binding materials is carried out in a ball mill with central unloading CBM 3200x4500

(Ukraine). This mill is designed for crushing and fine grinding of ferrous, non-ferrous, and rare metal ores, granulated blast furnace slag, limestone, dolomite, and other materials. It has a productivity of 42–121 tons per hour, with a relatively low weight of 160 tons (Table 1).

Table 1. *Characteristics of the ball mill CBM 3200x4500*

The name of indicators	**Indicators**
Drum diameter, mm	3200
Drum length, mm	4500
Nominal volume, m^3	32
Electric motor power, kW	800
Operating voltage, V	6000
Drum rotation frequency, s^{-1}	0,33
Productivity, t/h	42–121
Weight with electrical equipment, t	160
Maximum mass of grinding media, t	61

The industrial use of a disintegrator in mining practice was first carried out at the Shokpak deposit (Northern Kazakhstan) (Ghorbani et al. 2016). For 10 years, the *DU-65* industrial installation was in operation, making it possible to simulate the material processing mode, change rotors from 4 to 3 rows, and engines with a power of 200 to 250 kW. The material was activated by rotors with a protective layer. The installation was located in a separate building next to the backfill complex on three levels with a base area of 5–7 m.

The equivalent of 1 kg of standard M-400 cement was 4 kg of activated acid blast furnace tailings. Fast-acting devices are more effective, for example, disintegrator-activators type DU-65 (Disintegrator company, Estonia) and a vertical vibration mill type MVV-0.7 (Figure 6) (Ukraine).

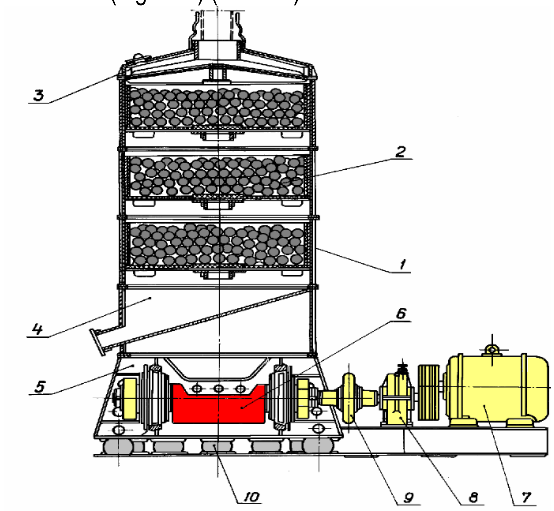

Fig.6. Vertical vibration mill MVV-0.7: 1 – housing, 2 – grinding chamber with grinding bodies; 3 – loading section, 4 – unloading section; 5 – drive section, 6 – unbalanced drive, 7 – electric motor; 8 – gear-synchroniser; 9 – elastic coupling; 10 – elastic supports

The DU-65 type disintegrator-activator provided productivity when crushing material with a density of 2–3 g/cm^3, at rotor speeds of 12000 min–1–10 kg/h, the maximum initial particle size of the processed material was 2.5 mm, the maximum humidity of the crushed material was 2%. Activity equivalent is the amount of activated binder material from waste that is equivalent to cement in binder properties. It is determined by an indirect method based on the rational ratio of binding materials.

The feasibility of using the simplex planning method has been proven, which allows one to search for the optimum taking into account several criteria. This leads to a slight increase in the number of experiments, because the movement towards the optimum in simplex planning occurs in a zigzag, and not along a gradient, as, for example, in the Box-Wilson method (Iordanov et al., 2020).

Mechanical activation of binding materials is carried out in grinders, for example, a ball mill with central unloading CBM 3200x4500 (Ukraine). However, the most effective are high-speed devices, for example, disintegrator-activators type DU-65 (Disintegrator company, Estonia) and a vertical vibration mill type MVV-0.7 (Ukraine) (Figure 7).

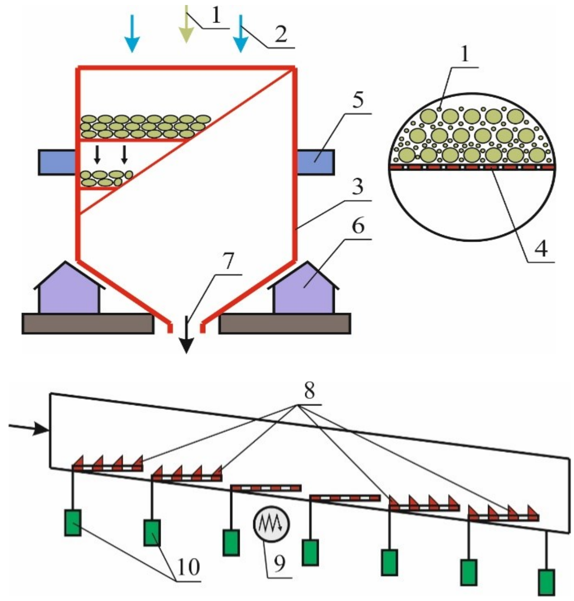

Fig. 7. Vibration activation of the components of hardening filling mixtures: a – vertical vibration mill: 1 – slag; 2 – water; 3 – chopper; 4 – sieve; 5 – vibrator; 6 – vibration dampers; 7 – activated slag; b – vibrating screen: 8 – teeth; 9 – vibrator; 10 – insulating supports

At the same time, the design becomes more complicated. For a hardening backfill mixture, the fineness of the slag grinding has a significant impact on the strength of the artificial mass. With the same consumption of binder material, the strength of the control samples, in which the fineness of grinding granulated blast furnace slag was 88% of the class - 0.074 mm, is 5 times greater than with a fineness of the formation of artificial masses.

Results and discussion

The energy consumption for activation during the process of delivering mixtures in the installation was 0.15-0.22 kW/m^3 of the mixture when supplied over a distance of 2.0 km. The average speed of the mixture through the pipeline was 2.5-3.0 m/s. The mixture was transported without adding water with a cone settlement of 9 cm. In the presence of elastic supports and vibration exciters, a dynamic calculation of the structure is also required (Figure 8).

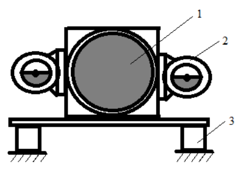

Fig.8. Pipeline section 1 with vibration exciters 2 and shock absorbers 3

At the same consumption of binder, as a result of vibration, the strength of the backfill mass increased by 20-25%. The driving force of the exciter was 2-5 kN, the vibration amplitude of the pipeline was 0.5-2.0 mm, and the vibration frequency was 10-20 Hz. One pathogen affected a section of the pipeline 200-220 m long. Gravity and vibro-gravity pipeline transport of hardening filling mixtures are close in the calculation of technological parameters. The advantage and difference is that with vibrating gravity transport, the resistance to the movement of the mixture through the pipeline is reduced and the strength of the filling is increased.

Deviations for these reasons from the mode of preparation, transportation and placement of the mixture cause delamination in the pipeline (Kucha et al., 2013).

Research has established that heap leaching tailings or crushed rocks can be used as an additive to the hardening filler. Moreover, the strength of the artificial massif with the addition of heap leaching tailings is higher than with the use of crushed rocks at the same slag consumption per 1 m^3 of backfill. After leaching and washing, the tailings are transported to the stowage complex. At the same time, crushed rock is fed.

The dosage is carried out in a certain ratio with sand and enters the mixer, into which ground blast furnace slag and mixing water are supplied in the required quantity. Technical and economic calculations have shown that, taking into account the existing technology for production and delivery of backfill material to the place of laying, the most rational is the scheme with crushing rock waste and transporting it through pipelines to underground man-made voids. This scheme is characterised by ease of organisation and maintenance, high performance, and operational reliability (Figure 9).

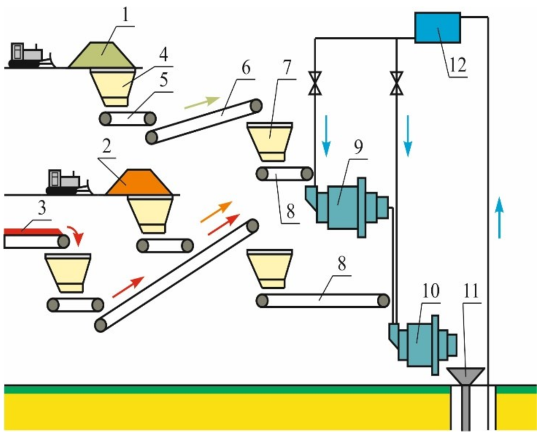

Fig.9. Technological diagram of the backfill complex for preparing a hardening backfill mixture using crushed rocks and heap leaching tailings: 1 – blast furnace slag; 2 – loams; 3 – breed with DSC; 4 – receiving bunker; 5 – feeder-dispenser; 6 – conveyor; 7 – consumable hopper; 8 – dispenser; 9, 10 – ball and rod mills, respectively; 11 – receiving funnel; 12 – water container

To stabilise the strength of hardening filling mixtures based on slag binder, the authors determined the optimal fineness of its grinding, which for the conditions under consideration is 50 – 60%, containing particles (n, %) with a particle size of 0.074 mm. The maximum strength of the artificial massif using the vibration-gravity method of its transportation is achieved at a concentration of solid inert filler and binder K = 0.80–0.85. The most effective tool for activating the ingredients of a hardening mixture is a disintegrator, which provides an increase in the activity of binders by up to 40%.

Complex activation includes vibration activation on the vibrating screen, mechanical activation in the mill, electrochemical water treatment, and vibration of the hardening filling mixture during transportation
(Figure 10).

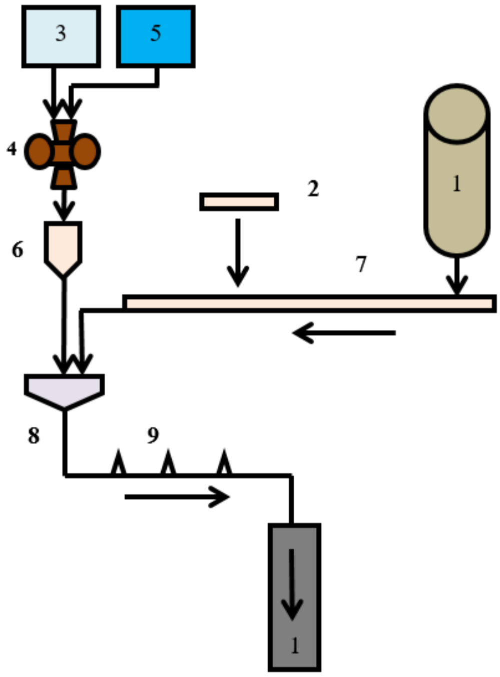

Fig. 10. Scheme of activation of the components of hardening mixtures during their production and transportation: 1 - cement bunker; 2 – vibrating screen of inert aggregates; 3 – blast furnace slag; 4 – disintegrator-activator DU-65 (Disintegrator company, Estonia); 5 – activated mixing water; 6 − vertical vibrating mill MVV-0.7 (Ukraine); 7 – conveyor; 8 – mixer; 9 – vibrators; 10 − man-made void (spent chamber)

Activation in a disintegrator provided an increase in strength 25–30% greater than treatment in a ball mill. Yield up to 55% active grade in combination with a vibrating mill increased yield to 70%, allowing the activated local binder to compete with cement.

The disintegrator simultaneously crushed, dispersed and activated blast furnace acid metallurgical slag in order to reveal its astringent properties in the process of preparing hardening mixtures during the development of a deposit with the filling of technological voids. It is installed in the technological chain after the disintegrator. Due to the high oscillation frequency, the crushed material experiences one to two orders of magnitude more impacts per unit time than in ball mills. The research results for an initial material size of 0–10 mm are given below. Vibration parameters: vibration amplitude – 6.5 mm; the magnitude of the driving force is 190.8 kN. Mill productivity for the initial product is 9.0–10.0 t/h. The rational mode of the vibrating mill is determined by the interconnection of the modes that make up the technological chain of the filling complex. The results of grinding the material at different grinding sizes and the yield of the active fraction are given in Table 2.

The activation coefficient for the disintegrator-activator in comparison with the ball mill used at the deposits of the Joint Stock Company "Virgin Mining and Chemical Combine" (JSC "Tselinny Mining and Chemical Combine", Republic of Kazakhstan) is equal to 1.25.

Table 2. *Material grinding results*

Grinding stage	Residue on the sieve, % at grinding coarseness, mm									Active faction
	1,60	1,00	0,63	0,40	0,315	0,20	0,10	0,10	0,074	
I	8,69	3,81	3,10	2,35	1,16	1,84	1,27	3,23	3,90	70,65
II	0,77	1,50	2,53	3,05	2,15	3,67	2,05	2,05	6,79	71,58
III	0,26	0,82	1,32	2,10	1,85	3,63	2,11	2,11	6,28	75,58

The *MVV-0.7* vertical vibratory mill for grinding granulated slag is used in the technological chain after the disintegrator. In it, the crushed material experiences one to two orders of magnitude more impacts per unit time than in ball mills.

The vibration amplitude of the mill is 6.5 mm, and the magnitude of the driving force is 190.0 kN. Impact loading of the crushed material in this mill with minimal abrasion allows for deep activation, which leads to an increase in the period the material remains in the active state (Lysychenko et al., 2011, Lyashenko, et al., 2021). Disintegrators are very effective at finely grinding soft rocks. At the mining enterprises of Central Mining and Chemical Plant JSC, the Republic of Kazakhstan, devices for vibration, mechanical and electrochemical activation of mine water are used to obtain a hardening backfill mixture with a strength of 0.2–1.2 MPa using local materials**.**

When producing a low-strength filler, it is necessary to ensure fine grinding, destruction of loosely bound pieces of filler and a stable transportation mode. This is carried out by vibration activation of inert materials, mechanical activation of binders before mixing, vibration activation of the hardening filling mixture during its transportation, and electrochemical activation of water.

It is advisable to carry out vibration activation of the hardening filling mixture during its transportation through pipelines. The rational mode of the vibrating mill is determined by the interconnection of the modes that make up the technological chain of the filling complex (Mac Carthy et al., 2016, Lyashenko, et al., 2022). Vibration activation of inert fillers during screening is possible in the case when stress concentrations are created in a piece of material sufficient for its destruction. The activation efficiency is determined by an indirect method based on the rational ratio of binders (Table 3).

It is advisable to carry out vibration activation of the hardening filling mixture during its transportation through pipelines. The rational mode of the vibrating mill is determined by the interconnection of the modes that make up the technological chain of the filling complex (Mac Carthy et al., 2016, Lyashenko, et al., 2022). The formula for determining the activation coefficient, for example, of a disintegrator is:

$$K_a = 1 + \frac{Э_м - Э_{ду}}{Э_м}, \qquad (16)$$

where $Э_м$, $Э_{ду}$ – are the equivalent of the activity of the material during grinding in mills and a disintegrator, respectively.

Table 3. Slag activity indicators

Mining enterprises	Activation devices	Binders, kg/m³		Water, l/m³	Filler, kg/m³	Activity equivalent
		slag	activator			
Pervomaisky GOK LLC (Ukraine)	Mill	400	Plaster 20	320	Sand 1200	20
PJSC "Zaporozhye Iron Ore Plant" (Ukraine)	Mill	400	Cement 50	380	Sand 1270	8
JSC "TsGKhK" (Republic of Kazakhstan)	Mill	400	Cement 50	360	PGS+breed 1350	8
	Disintegrator DU-65	190–220	Cement 60	380	Sand 1360	6.6–10.0
		220–300	Cement 30	380	Sand 1350	4.0–4.6

Note: ASG is a sand-gravel mixture

In comparison with the ball mill used at the uranium deposits of JSC Central Mining and Chemical Plant, this coefficient according to formula (16) is equal to:

$$K_a^{ду} = 1 + \frac{8-6}{8} = 1,25.$$

Implementation results. The amount of costs for environmentally friendly technology depends on the achieved preparation and transportation of hardening filling mixtures; they can be recommended for mining enterprises in developed mining countries of the world. The rational mode of the vibrating mill is determined by the interconnection of the modes that make up the technological chain of the filling complex. The use of vibration, mechanical and electrical activation of the components of the hardening backfill mixture at mining enterprises leads to an increase in the activity of binders and substandard materials by up to 10–40% for each apparatus (Naduty et al., 2012, Reiter et al., 2014). The authors proposed and implemented new technological schemes of backfill complexes for the disposal of waste from mining and metallurgical production into the underground goaf as components of hardening backfill mixtures, which gave positive results in the underground development of ore deposits of complex structure in Ukraine, Northern Kazakhstan, Germany, and other developed mining countries (Serdyuk et al., 2011, Rysbekov et al., 2019).

Effectiveness of developments. And finally, based on the research carried out by the authors, a theoretical generalisation was carried out and a solution was offered to the scientific problem of developing the theory of interaction of grinding bodies in the grinding chambers of mills and increasing the efficiency of equipment for fine grinding of rocks, which is of great importance for the mining industry (Stupnik et al., 2022, Zelinsky et al., 2022). Prerequisites are also being created for solving regional environmental challenges for balanced resource conservation during the extraction and processing of mineral resources (Sotskov et al., 2019).

The efficiency of choosing parameters and areas of application of nature- and resource-saving technologies for underground mining of ore deposits based on process intensification is carried out according to the criterion of reduced profit, taking into account the preservation of the earth's surface, as well as the damage caused (or prevented) (economic consequences) to the environment and the costs of protecting the population, living in the zone of influence of mining enterprises (mining and processing), according to the Golik-

Lyashenko analytical model (Serdyuk et al.,2011, Report et al., 2023).

The analytical model consists of two blocks: geomechanical and economic. The model is built on the basis of the results of many years of research on conducting a complex of research works on the underground development of complex ore deposits in energetically disturbed massifs (Stupnik et al., 2018, Stupnik et al., 2022).The model provides basic calculation formulae for substantiating the safe and effective parameters of the chambers, taking into account the stability of their outcrops (Table 4).

Table 4. *Safe parameters of chambers for ore deposits*

Name of parameters	Calculation formulae
1.Equivalent spans at outcrops, m:	
correct shape;	$L_{экв} = \frac{a \cdot в}{\sqrt{a^2 + в^2}}$
irregular shape	$L_{экв} = \frac{2{,}5 \cdot S}{P_0}$
2. Outcrop stability criterion, m	$L_{экв} = L_{эдоп} = \frac{L_{эо}}{1{,}1}$
3. Stable spans, m:	
horizontal	$L_{г.экв} = \frac{a \cdot в}{\sqrt{a^2 + в^2}}$
vertical	$L_{в.экв} = \frac{a \cdot H}{\sqrt{a^2 + H^2}}$
4. Equivalent span ($L_{эо}$, м) taking into account the existence time of outcrops (t, months)	$L_{эо}^2 \cdot t = const = A$
5. Equivalent spans for laying, m	
horizontal;	$L_{г.экв} = \sqrt{\frac{2\sigma_{из} \cdot h_{сл}}{\gamma_з \cdot K_з}}$
vertical	$L_{в.экв} = \frac{2C_м}{\gamma_з \cdot K_з} ctg\left(45^{\circ} + \frac{\rho}{2}\right)$
6. Stability of outcrops, m:	
length (a);	$a = \frac{L_{г.экв} \cdot b}{\sqrt{b^2 + L_{г.экв}^2}}$
width (b);	$b = \frac{L_{г.экв}^2 \cdot a}{\sqrt{a^2 + L_{г.экв}^2}}$
height (H)	$H = \frac{L_{г.экв} \cdot a}{\sqrt{a^2 + L_{г.экв}^2}}$

Note. The formulae indicate: S и P_0 – area and perimeter of the outcrop, m^2 and m, respectively; A is a constant value, the value of which depends on the properties of the rock mass and is determined from experience, units (for complex-structured ore deposits of the State Enterprise SE “SkhidGZK” , Ukraine in energy-disturbed massifs, the value A varies from 26800 (highly fractured massif) to 220000 (weakly fractured massif) with horizontal when the massif is exposed and from 75000 (highly fractured massif) to 1060000 (weakly fractured massif) – when hanging wall rocks are exposed); $\sigma_{из}$ – is the bending strength of the fill, t/m^2; $h_{сл}$ – thickness of the lower monolithic layer of the fill (in calculations it was assumed $h_{сл}$ = 4 м); $\gamma_з$ – filling density, t/m^3; $K_з$ – safety factor (in calculations it is assumed $K_з$ = 3); $C_м$ – coefficients of adhesion between the backfill and ore, t/m^2; ρ – angle of internal friction (in calculations it was assumed ρ = 32^0).

For the safety of mining operations in the zone of influence of the voids of the spent chambers, the following is performed:

- forecast of the stressed-strained state (STS) of the mountain massif and assessment of the conditions for the dynamic manifestation of mountain pressure;
- organisation of the system of geomechanical monitoring of the VAT of the mountain massif and the stability of open chambers;
- equipping mines with equipment and devices for safe operation of mines;
- training of mine staff for monitoring and control of VAT of the mountain massif.

The economic block of the analytical model takes into account the costs of protecting the population (including costs of environmental protection, rehabilitation of polluted and disturbed areas, human health, etc.) living in the zone of influence of mountain objects:

$$P = \sum_{i=1}^{n}\left[\left(T_{dr} - S_{dr} \pm (D + Z_n)\right)\right]\frac{1}{1+\mathrm{E}^{t-1}} \cong max, \quad (17)$$

where P is profit from obtaining final products from metal-containing ores, money. unit; T_{dr} – total extracted value of final products from metal-bearing ores, UAH. unit; S_{dr} – total costs of mining and obtaining final products, money. unit; D – total damages (economic consequences) caused (–) to the environment or preventing its pollution (+) taking into account the costs of protecting the population living in the zone of influence of mining enterprises (Z_n), gros. unit; E is the cost and profit discount factor in time *t* of the application of the evaluated technology, fractions of units.

A distinctive feature of the proposed model is the accounting of costs for the protection of the population living in the zone of influence of mining enterprises. Taking into account the national importance of the extraction of uranium raw materials, the government of Ukraine adopted a number of special resolutions aimed at strengthening radiation and social protection of the population with a total budget funding of over UAH 200 million. The main scientific and practical results of the mentioned accounting are most fully explained on the example of the city of Zhovti Vody, Ukraine (Serdyuk et al., 2011; Dudar, 2023).

In our opinion, the following new scientific and methodological provisions deserve attention:

It has been shown that when the crushed material is exposed to shock pulses with amplitudes greater than 250 and durations less than 0.01 s, the walls of cracks contained in particles can be considered as thin homogeneous plates with elastic and dissipative properties, while the crack wall motion is described by the Lagrange equation of the second kind for a system with one degree of freedom.

It has been established that the use of the developed UVT design allows: to reduce the energy intensity of transportation to 0.25–0.30 kW h per 1 m3 of mixture; to increase the length of the pipeline section to 150–200 m, productivity by 1.8–2.0 times, and the strength of the artificial massif by 20–25%; to ensure reliable delivery of mixtures with a standard cone slump of 10–13 cm, containing 0.10–0.35 dispersed particles by weight and having a solid concentration of K = 0.80–0.85, over a distance 20 times greater than the filling height of the vertical column.

It was determined that the rational solid concentration in the hardening filling mixture is 0.80–0.85, vibratory gravity transport eliminates stratification of the mixture during its transportation, and allows to increase the strength of the artificial massif by 20–25%. It is substantiated that a decrease in the frequency of forced oscillations of motor-vibrators with a constant vibration displacement coefficient Г leads to an increase in the length of the section served by one (pair of) vibration exciter (an increase from 150 to 200 m with a decrease in frequency from 150 to 100 rad/s). The efficiency of the impact of elliptical oscillations of the pipeline on reducing the resistance to movement of the hardening backfill mixture with an increase in the maximum length of the horizontal section of the pipeline compared to gravity transport is noted. The optimal size of the waste is established taking into account the costs of crushing, pipeline transport, and the density of their placement in the spent chambers and it is within 25-35 mm. To stabilise the strength of hardening backfill mixtures on a slag binder, the authors determined the optimal fineness of its grinding, which for the conditions under consideration is 50 - 60%, containing particles with a size of 0.074 mm.

Conclusions

Mathematical and physical modeling was performed, and the parameters of the installation of vibratory gravity transport (VGT) of hardening backfill mixtures were calculated. Taking into account the obtained dependencies, the following were determined, performed in the order given below: the frequency and minimum amplitude of forced oscillations of the pipeline; the diameter of the pipeline and specific pressure losses; the delivery range; the length of the section and their number; the parameters of the elastic element of the support; their number; the magnitude of the forcing force of the vibration exciter; and the power of the drive (motor-vibrator).

Vibratory transport units are recommended to increase the activity of solid components (binder and inert filler) of the hardening backfill mixture. It is shown that when using sand-slag hardening backfill mixture, the rational slag consumption is about 400 kg/m^3. When using crushed rock additives, slag consumption can be reduced to 300 kg/m^3, and taking into account the use of GMZ tailings – to 200 kg/m^3. The use of UVT increases the activity of solid components of the hardening backfill mixture by 10-15% and ensures the supply of the backfill mixture to a distance 15-20 times greater than the height of the vertical stack. In accordance with the calculation method, UVT was created and introduced into production at JSC *Tselinny* Mining and Chemical Plant, Northern Kazakhstan.

A new set of technical means is proposed for activating a binder (granulated blast furnace slag), inert fillers (screening product of substandard materials) and mixing water in the manufacture and transportation of hardening backfill mixtures. The use of vibration, mechanical and electrical activation of the components of the hardening backfill mixture at mining enterprises leads to an increase in the activity of substandard materials by up to 10–40% for each device. In particular, enrichment of inert materials on the *GV-1.2/3.2* vibrating screen (Ukraine) increases the activity by 15–20%. Activation of binders (granulated blast furnace slag) in the *MVV-0.7* vertical vibrating mill (Ukraine) and the *DU-65* disintegrator (Dezintegrator, Estonia) increases the activity of the binder by 20–25%, with the output of the active class of fractions with a size of 0.074 mm – by 55% versus 40% in ball mills.

It is proposed to continue prospective research and provide funds (at the expense of enterprises, local and central government bodies) for conducting scientific substantiation and developing preventive measures to minimise the negative consequences on human health from exposure to heavy metals and environmental protection, taking into account the characteristics of their combined impact on the population and workers in the mining and metallurgical industry.

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