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TRANSPORTATION OF CONCENTRATION AND LEACHING TAILINGS IN UNDERGROUND MINING OF METAL DEPOSITS

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ABSTRACT

Purpose. The article aims to substantiate efficient parameters of resource-saving technological processes ensuring optimal environmental and economic indices of concrete mixtures transportation under the force mode and changes of the transported mass parameters depending on transportation conditions.

Methods. The complex method of investigation includes generalization and analysis of the theory and practice of mixtures transportation, theoretical and industrial research into the processes associated with long-haul delivery of mixtures, engineering forecasting, mathematical simulation with alternative calculation variants for the purpose of developing recommendations.

Findings. Parameters of concentration and leaching tailings transportation under the force mode of a vibration wire were calculated in detail for the case of the haul length exceeding potential of the gravity flow. Calculation schemes for determining head losses and the flow critical velocity are created by alternative methods and ranked according to the reliability degree.

Originality. Basic points of the new method for controlling indices of mixture preparation and transportation by changing the head and the feed rate of mixtures are defined for combined mineral mining.

Practical implications. Solving the problem of hydromixture transportation under the force mode by joint application of accumulated industrial experience and simulation of delivery processes for combined mineral mining in order to achieve a complex environmental and economic effect.

Keywords: *deposit, hydromixture, transportation, pipeline, ore, simulation, vibration*

1. INTRODUCTION

Civilization development is accompanied by growing metal consumption to meet the demands in consumer goods. With technological capacities developed and mining technique improved, poorer and more complex ores are involved, while the number of voids in the Earth's crust and technogenic reserves of tailings on the surface are increasing. Modern mining production is characterized by intensive transfer of active reserves of metal materials into non-active ones, while some metals are lost in tailings both on the surface and in off-grade ores in situ.

In the middle of the last century, there appeared a technology which aimed at solving this problem by replacing extracted ores by certain materials, among which consolidating concrete mixtures were the most efficient. High cost of consolidating mixtures necessitated replacement of expensive components by cheaper and more available ones like tailings of ore concentration and processing, which can be used as both aggregates and binders.

Wider application of tailings in mixture production is hindered by presence of metals that cannot be fully extracted from tailings. The problem cannot be solved by conventional ore processing methods. Metal extraction to background levels by leaching in such activators like disintegrators has been introduced lately.

Underground metal leaching technology was implemented a bit later. It allowed not only to increase the mineral base due to the introduction of formerly off-grade ores but also to reduce the volume of voids caused by mining operations. One side effect of the given technology is extraction of up to 40% of poor ores, which greatly increases the amount of waste on the earth surface.

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2. ANALYSIS OF CURRENT STUDIES

Recent publications have raised issues of improving underground mining technologies and outlined current conditions of mining production, namely:

– increased volumes of ore processing tailings (Adibi, Ataeepour, & Rahmanpour, 2015; Morkun & Morkun, 2018);

– selective extraction of rich components accompanied by losing metals in off-grade ores and processing tailings (Golik, Komashchenko, & Morkun, 2015; Sinclair & Thompson, 2015);

– limited possibilities of utilizing concentration and ore processing wastes for manufacturing concretes (Lyashenko, 2015);

– deficiency of technologies for deep metal extraction from ores (Golik, Komashchenko, & Morkun, 2015; Rylnikova, 2017).

Metal extraction from chemically recovered ores can be improved by applying a combined technology involving the following elements of a single technological process:

– processing by ultrasonic technology (Morkun, Morkun, & Tron, 2017; Morkun & Morkun, 2018);

– leaching of metals from off-grade materials unsuitable for conversion in underground blocks, piles and activators and for using tailings in consolidating mixtures (Krupnik, Shaposhnik, Shaposhnik, Nurshabekova, & Tungushbayeva, 2017).

Further increase in metal output brings about the problem of transportation of concentration and leaching tailings to places of their use and storage. Concentration tailings should be transported from places of original concentration to the metal leaching site and further to sites of preparation and use of consolidating mixtures either after concentration completion or later as mature tailings (Golik, Komashchenko, & Morkun, 2015).

This problem can restrict metal production potential and is topical in current market conditions.

Concentration tailings in the form of concrete mixtures or hydromixtures are transported with the solid-liquid ratio (S:L) of 1:6 and the tailings density not less than 1.25 t/m^3.

Concrete mixtures are characterized by humidity, which determines their liquescence and other parameters. Concrete mixtures should meet the following requirements: transportability over long distances, minimized expenses, environmental considerations, etc. (Dmitrak & Kamnev, 2016; Dmitrak, 2017).

Mobility of mixtures is especially acute in underground mining, in particular, if there are adjusted mine workings with reverse inclination.

Mixture transportation is improved with the force impact on a pipeline. The resistance to transportation in the pipeline is compared to dynamic friction forces. With the full pipe of a considerable length, resistance to transportation exceeds the mixture weight and discredits the process itself. When conveying vibrations to the pipeline, resistance falls greatly, thus increasing the impact of the head flow (Komashchenko, Vasil'yev, & Maslennikov, 2016; Golik, Morkun, Morkun, & Gaponenko, 2018).

Concrete mixtures are significant in the mining output. They are characterized by humidity, which determines congelation, liquescence and other parameters. That is why technologies using water as a transportation means are excluded, while non-water technologies are preferred (Yermolovich & Yermolovich, 2016).

The problem becomes topical in underground mining, especially when mine workings with reverse inclination are applied. Combined mineral mining implies time-space oriented combination of elements of the technological cycle, which differ from traditional work arrangement in the following:

– filling voids caused by rich ore mining with consolidating mixtures and creating conditions for underground leaching;

– differentiating mixtures according to strength not only within stope groups, but also within a stope;

– controlling indices of mixture preparation and transportation (the complex capacity, the driving force and frequency of forced vibrations of the pipeline, solid material concentration);

– regulating indices of hydromixture transportation by changing the head and the mixture feed rate.

Research into the mining sphere under consideration is aimed at substantiating a scheme of transporting concrete mixtures under the force mode and simulating dynamics of changing parameters of the transferred mass depending on transportation conditions (Vintró, Sanmiquel, & Freijo, 2014).

The set goal is achieved by solving a number of tasks:

1. To estimate the potential of applying hydromixture transportation in underground mining.
2. To define parameters of efficient hydromixture transportation under the force mode according to length and reliability criteria.
3. To substantiate efficiency of the applied technology of hydromixture haul under the force mode in combined mining with filling voids with consolidating mixtures and metal leaching.
4. To develop recommendations for applying hydromixture haul technology under the force mode.

3. MATERIALS AND METHODS

To haul filling mixtures under the ground, gravity, gravity-pneumatic and vibration schemes of pipeline transport are applied. The first scheme provides stable 850 m haul, the second one – 1200 – 1500 m haul, the third one has not been studied well enough.

The haul length is increased by the compressed air feed into the pipeline. The portions of the consolidating filling mixture divided by air gaps are formed in the pipeline, while the speed of mixtures movement rises.

Both methods are reliable enough when the ratio of the vertical and horizontal parts of the pipeline does not exceed 1/5. Experiments of hydromixture transportation are carried out in a hydro-transport installation, which includes pipelines, controlling mechanisms and controlling measuring devices.

The studied processes are simulated in the 5.5 m pipeline. The critical speed is determined by hydromixture consumption at the moment of formation of the1mm thick solid layer with the solid-liquid ratio: 1:1.0; 1:1.5 and 1:2.0. The studied material includes fine sand (0.1 – 0.06 mm) and coarse dusty fractions with the plasticity index of 1 – 7%.

Parameters of hydromixture transportation in underground mining of non-ferrous, rare and thermal metal ores are substantiated by simulation of their transportation under the force mode according to the length and reliability criteria.

The obtained data are used in mathematical simulation of the processes with the help of alternative calculation variants for developing recommendations in certain conditions (Chugh & Behum, 2014).

Mathematical simulation of hydromixture transportation in underground mining under the force mode is described depending on the haul mode in the pipeline.

In case of the gravity and gravity-pneumatic schemes, the motion equation of the hydromixture with a good adequacy degree meets the Bernoulli equation for the real liquid (hydromixture):

$$Z_{in}+\frac{p_{in}}{\rho g}+\frac{V_{in}^2}{2g}=Z_{out}+\frac{p_{out}}{\rho g}+\frac{V_{out}^2}{2g}+\Delta h, \qquad (1)$$

where:

Z_{in}, Z_{out} – are levels of the pipeline inlet and outlet correspondingly towards the vertical axis as to the chosen reference point;

p_{in}, p_{out} – are hydromixture stresses at the inlet and the outlet;

V_{in}, V_{out} – are averaged motion velocities along the cross-section of the inlet and outlet;

ρ – is the average density of the hydromixture;

Δh – is the loss of head in the pipeline.

The value $p/\rho g$ in equation (1) is a piezometric height, and $V^2/2g$ is the height of the velocity head.

To determine hydromixture parameters at the pipeline outlet, the equation of flow continuity is used:

$$V_1 S_1 = V_2 S_2 = Q = const, \qquad (2)$$

where:

V_1, V_2 – are flow velocities in some flow sections;

S_1, S_2 – are areas of corresponding flow sections.

The impact of the hydromixture heterogeneity causes irregular distribution of velocities in the flow cross-section of the pipeline. Thus, the hydromixture motion equation will look like:

$$Z_{in}+\frac{p_{in}}{\rho g}+\frac{\alpha_1 V_{in}^2}{2g}=Z_{out}+\frac{p_{out}}{\rho g}+\frac{\alpha_2 V_{out}^2}{2g}+\Delta h, \qquad (3)$$

where:

α_1, α_2 – are coefficients characterizing heterogeneity of velocity distribution (Coriolis coefficients) at the pipe inlet and outlet correspondingly.

Coriolis coefficients are determined by experiment and they are equal to $\alpha_1 = 1.1$ at the inlet and $\alpha_2 = 1.05$ at the outlet of the 850 m pipe, with the level difference of the inlet and the outlet of 25 m and the 0.0078 m^2 cross-section.

Based on equations (2) and (3), we determine basic parameters of hydromixture flow in the pipeline.

Friction losses along the whole pipeline under the head transportation mode are calculated by the formula:

$$\Delta h=\lambda\frac{V^2 l}{2gD}, \qquad (4)$$

where:

λ – is the hydraulic friction coefficient;

V – is the average velocity of the hydromixture flow along the pipeline;

l – is the pipeline length;

D – is the pipe diameter.

The hydraulic friction coefficient is determined by the Reynolds number and relative roughness of the pipe or according to the graph (Bol'shakov, 1984):

$$\lambda=F\left(R_e,\frac{\Delta}{D}\right), \qquad (5)$$

where:

R_e – is the value of the Reynolds number;

Δ – is the absolute roughness of the pipe.

In case of hydromixture transportation under the gravity or the gravity-pneumatic schemes, the equation of the hydromixture consumption in the pipe for the one-dimensional flow is determined by dependency (Adibi, Ataeepour, & Rahmanpour, 2015):

$$Q=S\cdot p_{los}\sqrt{\frac{2}{K\rho\sqrt{p_{los}^2+p_{crit}^2}}}, \qquad (6)$$

where:

S – is the area of the flow cross-section;

K – is the pressure loss during the hydromixture motion;

ρ – is the average density of the hydromixture;

p_{los} – is the pressure loss in the pipe;

p_{crit} – is the critical pressure under which hydromixture motion switches from the laminar mode to the turbulent one.

Pressure losses along the flow cause friction and hydromixture head in the pipe can be described by the following equation (Jang, Topal, & Kawamura, 2015):

$$p_{los}=f\frac{(l+L_{lr})\rho Q|Q|}{2RS^2}+\rho g\left(h_{out}-h_{in}\right), \qquad (7)$$

where:

f – is the coefficient which depends on the Reynolds number and the pipe form;

L_{lr} – is the aggregate length of local resistances;

R – is the hydraulic radius of the pipe cross-section;

h_{in} – is the level of the pipe start location;

h_{out} – is the level of the pipe end location.

As experiments show, in case of hydromixture transportation by the vibration scheme, the value of f coefficient reduces greatly by a factor of 2.0 – 2.5.

The experimental model of the hydromixture haul system was realized on the basis of mathematical equations. The model includes a pool filled with hydromixture, wherefrom it is fed to an accumulator with a centrifugal pump, local resistances in the form of elbows as well as a pipeline with a valve. A flow meter is in the reverse pipeline.

Characteristics of the simulated hydromixture are set at the pipe inlet. The simulation results with the step excitation, i.e. under the constant frequency of the pump revolution of 1300 r.p.m., are obtained.

At the first stage before the 120th second, the stabilizing reservoir is filled. This site is considered to be the initial filling with the hydromixture feeder started and it should be taken into account in designing the controlling system of the hydromixture return.

The second stage before the 270th second is characterized by the aperiodic transition process when the reverse pipeline is filled with hydromixture.

At the third stage, the hydromixture feed branch changes from the closed position into the fully open one, which results in redistribution of the consumed hydromixture filling the vessel in two directions.

To intensify hydromixture transportation, the mechanical oscillation action is applied increasing mobility and improving rheological properties of hydromixture. Yet, these impacts have drifting extreme dependencies which were investigated by a mathematical model of hydromixture motion designed in the form of a nonlinear dynamic system (Besedin, Trubayev, Panova, & Grishko, 2011).

Experiment results based on the suggested models are given below.

4. RESULTS AND DISCUSSIONS

At "Wismut" deposit (Germany), a consolidating mixture was fed by the vibration-gravity method for the distance exceeding the height of the vertical standpipe threefold (Komashchenko, Vasil'yev, & Maslennikov, 2016). At the end of the last century, while mining Shokpak-Kamyshovoye deposit (Kazakhstan), mixtures were hauled for the distance exceeding the standpipe by many times (Golik, Komashchenko, & Morkun, 2015).

In hauling mixtures for the distance of up to 2.5 km, the energy consumption was 0.15 – 0.22 kW/m^3. The transported mixture strength increased by 20%.

The installation was characterized by the following parameters: the diameter of the air tie-in is 40 mm, the pipeline diameter is 170 mm, the compressed air pressure in the overhead pipe is 6 MPa, the capacity is 60 m^3/h. Parameters of the vibration-haul installation include the driving force of 2 – 5 kH, the vibration amplitude of the pipeline of 1.2 – 2.0 mm, the vibration frequency of 6.0 – 13.0 Hz, and the impact of the exciter of 200 – 220 m.

Installation of vibration-pneumatic transport included a pipeline and vibrators. The system comprised a vertical site 175 m high and a horizontal site 2500 m long.

If the haul length of the filling by the traditional scheme rarely exceeds 1.5 km with the ratio of the vertical and horizontal parts of the pipeline being 1:5, under the current technology this ratio makes 1:20.

The transported mixture was composed of cement (up to 100 kg/m^3), blast-furnace slag (160 – 250 kg/m^3) and water (380 kg/m^3). The length of the mixture haul (horizontal lift) was 14 m – 2500. The flow velocity along the pipeline was 1.2 – 1.5 m/sec. The maximum capacity of the system was 100 m^3/h.

The pressure drop along the section made 0.6 – 1.0 MPa, grad $P = 3.0 – 5.0$ kPa/M under the gravity mode and 0.12 – 0.20 MPa, grad $P = 0.8 – 1.0$ kPa/M under the vibration mode.

Traditional transportation implies increased water consumption, which simultaneously decreases the mixture strength. Combination of the vibration and the pneumatic gravity technology can eliminate this drawback.

Basic parameters of the vibration haul include the transportation length (L), the standpoint height (H), the length of sections (L_1) and the location of the vibration exciter within the sector (L_2) (Fig. 1).

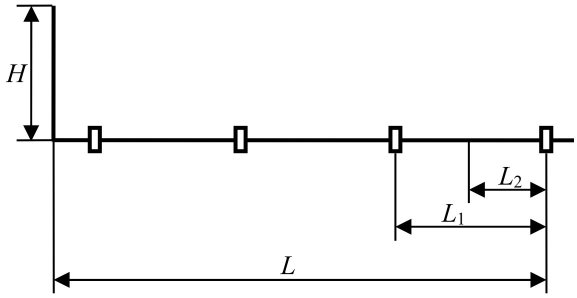

Figure 1. The vibration transportation scheme: L – the pipeline length, m; L₁ – the distance between vibrators, m; L₂ – the distance of the vibrator installation in the section, m

The minimum efficient amplitude of pipeline vibrations:

$$A_m = \frac{\rho_r - \rho_o}{\omega^2 \rho_r} g, \tag{8}$$

where:

ρ_r – is the density of the filling particles, kg/m^3;

ρ_o – is the density of the disperse medium, kg/m^3;

Mixture stratification is excluded under its velocity of 0.5 – 0.7 m/sec for mixtures with up to 5.0 mm particle sizes and under 0.7 – 1.0 for mixtures with 5.0 – 40.0 mm particle sizes (Golik, Komashchenko, & Morkun, 2015).

The inner pipeline diameter is:

$$D = 24.45 V_{av} d_{av} \sqrt{\frac{\rho}{\tau_o}}, \tag{9}$$

where:

V_{av} – is the average transportation velocity, m/sec;

d_{av} – is the average size of the transported material, mm.

The pressure loss in the horizontal section of the pipeline is:

$$\Delta\rho = \frac{\frac{158.73D}{D^4} + \frac{4\tau_o^1}{D\eta_1}}{\frac{6}{\eta} + \frac{1}{\eta_1}}, \tag{10}$$

where:

$\Delta\rho$ – are specific pressure losses, Pa/m;

$\tau_o{}^1$ – is the shear stress of the wall layer, Pa;

η_1 – is the viscosity of the thixotropically diluted wall layer, Pa·sec:

$$\eta_1 = 0.1\sqrt{\tau_o^1}. \tag{11}$$

The transportation length of the consolidating mixture is:

$$l = \frac{\rho_c}{\Delta\rho}, \tag{12}$$

where:

ρ_c – is the consolidating filling density, kg/m^3.

The distance between elastic supports is (Fig. 2):

$$l_{o1} = 0.5 l_o . \tag{13}$$

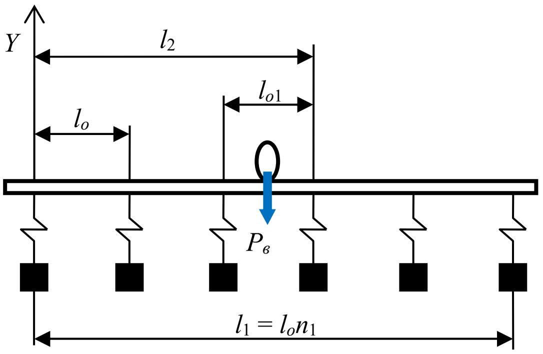

Figure 2. The scheme of the pipeline section

The value of the driving force of the vibration exciter is:

$$K = A\left(m_{pr} + m_v\right), \tag{14}$$

where:

K – is the moment of the eccentric weight of the vibration exciter;

m_{pr} – is the reduced mass of the pipeline considering the mixture.

The reduced mass of the pipeline is:

$$m_{pr} = \frac{1}{l_{pr}^2}\sum_1^n m_i l_i^2 , \tag{15}$$

where:

n – is the number of homogenous elements;

l_i – is the coordinate of the element m_i.

The value of the driving force of the vibration exciter is:

$$P = KW^2 . \tag{16}$$

The power to generate pipeline vibrations is:

$$N_1 = PWA \sin 2\varphi , \tag{17}$$

where:

φ – is the phase angle between the pipeline transfer and the driving force direction.

The phase angle is:

$$\varphi = arctg \frac{b_c S_T A}{Kw^2} , \tag{18}$$

where:

$S_T = \pi D l_1$ – is the inner surface of the pipeline sections;

b_c – is the coefficient of the mixture resistance to pipeline vibrations, cm^2.

The motor power of the section:

$$N_{dv} = \frac{N}{\eta_m} , \tag{19}$$

where:

η_m – is the efficiency coefficient of the elastic coupling.

The determined drive power is:

$$N_y = n_s N_{dv} , \tag{20}$$

where:

n_s – is the section number.

The driving force of the vibration exciter:

$$P = Kw^2 = m_g r w^2 , \tag{21}$$

where:

m_g – is the mass of the unbalanced part of the eccentric weight, kg;

r – is eccentricity of the unbalanced part of eccentric weight, m;

w – is the rotation frequency of the vibration exciter axis, c^{-1}.

The mass of the unbalanced part of the eccentric weight:

$$m_g = b_g \rho_g , \tag{22}$$

where:

S_1 – is the cross-section area, m^2;

b_g – is the width of the eccentric weight, m;

ρ_g – is the density of the eccentric weight material, kg/m^3.

The water pressure required for cleaning the pipe section l_y long is:

$$H_w \rho_w n = \Delta\rho l_y , \tag{23}$$

where:

ρ_w – is the water density, kg/m^3;

H_w – is the height of the standpipe filled with water, m:

$$H_w = \frac{3\Delta\rho l}{2}\rho_w g . \tag{24}$$

The minimum water volume for washing the pipeline is:

$$Q_w = \frac{\pi D^2}{4} H_w . \tag{25}$$

The pipeline is cleaned by compressed air with consumption:

$$D = 24.45 V_{av}\sqrt{\frac{\rho}{\tau_o}} , \tag{26}$$

where:

V_{av} – is the velocity of the mixture flow that ensures its movement, 2.0 – 4.0 m/sec;

P_1 – is the compressed air pressure in the network, Pa;

P_a – is the atmospheric pressure, Pa.

The head losses with transported hydromixtures are determined for various density of the mixture:

γ_r = 1.11; 1.13; 1.19; 1.22; 1.26; 1.32; 1.40 t/m^3.

Parameters of hydraulic resistance are determined by the least square method (Table 1):

$$100 J_r = a_1 V^2 + a_2 V , \tag{27}$$

where:

a_1, a_2 – are empiric coefficients;

V – is the average velocity of the flow, m/sec.

Table 1. Dynamics of hydraulic resistance

Sample	Density, t/m^3	Hydraulic resistance
1	1.00	$100I = 4.334V^2 + 2.158V$
2	1.11	$100I = 4.819V^2 + 2.323V$
3	1.13	$100I = 4.923V^2 + 2.347V$
4	1.19	$100I = 5.199V^2 + 2.385V$
5	1.22	$100I = 5.308V^2 + 2.523V$
6	1.26	$100I = 5.577V^2 + 2.384V$
7	1.32	$100I = 5.726V^2 + 2.747V$
8	1.40	$100I = 6.029V^2 + 3.007V$

Experimental data are compared with designed values:

$$J_r = J_b \frac{\gamma_r}{\gamma_b}, \tag{28}$$

where:

J_b – is the specific head loss with pure water moving;

γ_r – is the hydromixture density;

γ_b – is the water density.

$$J_r = J_b\left(1 + C_o\right), \tag{29}$$

where:

C_o – is a constant for the two-phase flow;

S – is concentration of the solid material in the hydromixture;

a – is the average density of the solid material considering the buoyant force:

$$a = \frac{\gamma_T - \gamma_b}{\gamma_w}, \tag{30}$$

where:

γ_T – is the density of the solid particles, t/m^3;

γ_b – is the density of water particles, t/m^3.

$$100J_r = \left(2.3 + 8.2F_r\sqrt{F^*}\right)aS + 100J_w, \tag{31}$$

where:

F_r – is the Frude number for the hydromixture flow:

$$F_r = \frac{V^2}{gD}, \tag{32}$$

where:

D – is the inner diameter of the pipeline, m;

g – is the gravity acceleration, m^2/sec;

F^* – is the Frude number for the part of the solid component:

$$F^* = \frac{W^2}{gd_{av}}. \tag{33}$$

Hydraulic losses with pure water transportation by the Darcy method are:

$$J_w = \frac{\lambda V}{D^2 g}, \tag{34}$$

where:

λ – is the hydraulic friction coefficient.

The value λ depends on the ratio of the Reynolds numbers (R_e) and maximum values of R_e^1 and R_e^2.

The value of R_e is:

$$R_e = \frac{VD}{v}, \tag{35}$$

where:

v – is the kinematic viscosity coefficient equal to $1 \cdot 10^{-6}$.

The value of R_e is within 75000 – 150000. The maximum value of R_e is:

$$R_e^* = \frac{10}{\bar{\Delta}} u R_e^{**} = \frac{500}{\bar{\Delta}}, \tag{36}$$

where:

$\bar{\Delta}$ – is specific roughness, (Δ/D);

Δ – is absolute roughness, (0.4).

To calculate λ, the following expression is used:

$$\lambda = \frac{8g}{C^2}, \tag{37}$$

where:

C – is the Chezy coefficient.

For the square resistance area:

$$C = \frac{R^{\frac{1}{6}}}{n}, \tag{38}$$

where:

R – is the hydraulic radius;

n – is the roughness coefficient of steel pipes (0.0125).

Experiments determined the values of losses comparable with the designed ones, while the specific losses with the velocity of less than 1.6 m/sec appeared to be higher than the designed values (Mwase, Petersen, & Eksteen, 2012).

Velocities along the pipeline are determined by the measured consumption of the hydromixture when the motionless silting layer is formed in the pipeline (Sinclair & Thompson, 2015).

Some alternative methods are used including:

1. S.Kh. Abilyants solution:
with $400 \cdot 10^{-6} \le d_{av} \le 400 \cdot 10^{-6}$ and $\gamma_T = 2.6 - 3.2$ t/m^3:

$$V_{kr} = \frac{207.14}{\lg R_{ew} + 5.5}\sqrt[3]{\left(1 - \frac{\gamma_b}{\gamma_n}\right)D\beta W}, \tag{39}$$

where:

R_{ew} – is the Reynolds number:

$$R_{ew} = \frac{wd_{av}}{v}, \tag{40}$$

β – is the constraint ratio:

$$\beta = \sqrt{20.25S^2 + \left(1 + S\right)^3} - 4.5S, \tag{41}$$

where:

S – is the volume density of the solid component in the hydromixture:

$$\frac{\gamma_r}{\gamma_w} - 0.4. \tag{42}$$

2. A.P. Yufin solution:
with $d_{av} \leq 0.15$ and $\gamma_T = 2.7 - 4.2$ t/m^3:

$$V_{kr} = 11\sqrt[3]{D}\sqrt[4]{W}\left(\frac{\gamma_r}{\gamma_w} - 0.4\right); \qquad (43)$$

and with $d_{av} \leq 0.074$ in the solid component of more than 50% and $\gamma_r \leq 1.25$ t/m^3:

$$V_{kr} = 15\sqrt[3]{D}\sqrt[4]{W}\left(\frac{\gamma_r}{\gamma_w} - 0.4\right)\varDelta_o^{0.1}; \qquad (44)$$

with 1.25 t/m$^3 \leq \gamma_p \leq 1.7$:

$$V_{kr} = 12.8\sqrt[3]{D}\sqrt[4]{W}\sqrt[3]{\frac{C_m}{C}}\Delta_o^{0.1};$$

$$\Delta_o = \frac{3d_{10}}{d_{90}}, \qquad (45)$$

where:

$\varDelta_o$ – is the heterogeneity condition:

$$\varDelta_o = \frac{3d_{10}}{d_{90}},$$

where:

C – is the weight body of the hydromixture;

C_m – is the weight body of the hydromixture with $\gamma_r = 1.25$ t/m^3.

3. A.P. Yufin solution:

$$V_{kr} = K_1 K_2 \sqrt[3]{D}\sqrt[4]{W}\left(\frac{\gamma_r}{\gamma_w} - 0.4\right), \qquad (46)$$

where:

$$K_1 = 8.075 + \frac{3.776}{d_{av} \cdot 10^4};$$

$K_2 = 1$ with $\gamma_p = 1.25$ t/m^3, with $\gamma_r \geq 1.25$ t/m^3,
where:

$$K_2 = \frac{12.58 - 6.86\gamma_p}{d_{av} \cdot 10^4}.$$

4. H.P. Sazonov solution:
with $0.05 \leq d_{av} \leq 1$:

$$V_{kr} = \sqrt{\frac{2gd_{av}\left(\gamma_T - 2\gamma_w + \gamma_r\right)}{10^3\gamma_w}}. \qquad (47)$$

Values of the obtained critical velocities are compared with the designed ones (Table 2).

Table 2. Dynamics of hydraulic losses in transportation

Velocity, m/sec	Chezi coefficient, m$^{0.5}$/sec	Hydraulic friction coefficient	Head loss (designed)	Head loss (experiment)	Δ, %
1.0	38.5	0.05	5.8	6.6	–11.7
1.5	—	—	12.1	13.0	–6.8
2.0	—	—	21.5	21.7	–0.6
2.5	—	—	33.6	33.5	+0.5

Dependencies of head losses on the flow velocity determined by the experiment are interpreted in Figure 3. If the flow velocity increases, losses increase as well. Yet, it turned out that calculated and experimental head losses almost coincide (Rylnikova & Peshkov, 2014; Kachurin, Stas, Kalayeva, & Korchagina, 2016).

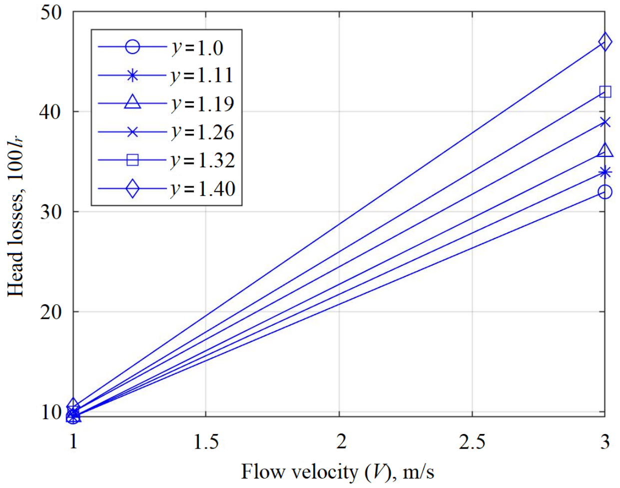

Figure 3. The graph of head losses dependency on the flow velocity

Values of critical velocities differ from the experimental ones by up to 34%. They are determined more accurately by the formula of A.P. Yufin.

The novelty of the obtained dependencies of hydromixture haul by pipelines under the force mode implies consideration of peculiarities of combined underground mining while changing the quality and quantity of hydromixtures fed for much longer distances than those in the traditional technology.

The capacity of haul A, t/h depends on the component size of hydromixture Q, %, and on the maximum value for the given conditions (Fig. 4).

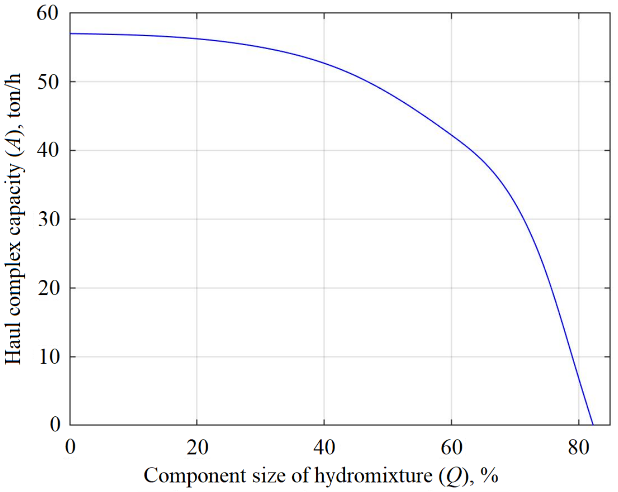

Figure 4. Dependency of haul complex capacity on the component size of hydromixture

Capacity of the pipeline transport under the force mode depends on the direction of the driving force of the vibration exciter (β) and the frequency of forced vibrations (f) (Fig. 5).

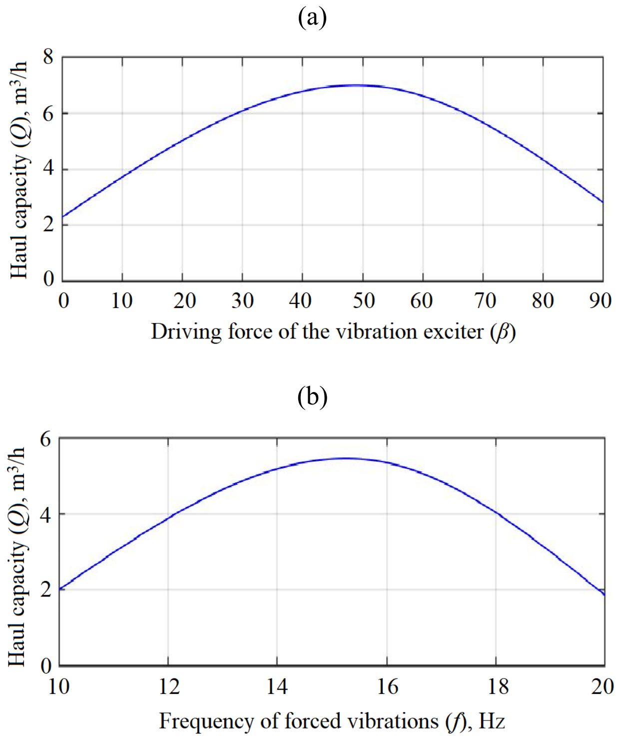

Figure 5. Dependency of the haul capacity on the direction of the driving force of the vibration exciter (a) and the frequency of forced vibrations (b)

The issue of hydromixture transportation is part of the global problem of humanization of resource exploitation (Chen, Lei, Yan, & Xiao, 2014; Ryzhova & Nosova, 2017). It influences the success of the applied combined technology including such elements of a technological cycle as rich ore mining accompanied by filling voids with consolidating mixtures and leaching metals from off-grade materials in piles and activators (Jang, Topal, & Kawamura, 2015; Sinclair & Thompson, 2015).

Optimization of hydromixture haul, reduction of expenses and environmental loads as well as other aspects of the mentioned problem become especially acute in underground mining of chemically extracted ores including most deficient ones of non-ferrous, rare and thermal metals (Sekisov, Shevchenko, & Lavrov, 2016).

Substantiation of the hydromixture haul scheme under the force mode and simulating dynamics of changing parameters of the transported mass depending on transportation conditions is an independent direction of developing modern innovative technologies (Doifode & Matani, 2015).

Solution of hydromixture transportation problem provides new possibilities to reduce mining and processing wastes in ore concentration and metallurgy (Urakayev & Yusupov, 2017; Zoteyev, Zubkov, Kalmykov, & Kutlubayev, 2017) that facilitates reduction of the technogenic load on the environment in mining regions (Kachurin, Kalayeva, Korchagina, & Stas, 2016; Morkun, Semerikov, & Hryshchenko, 2017).

5. CONCLUSIONS

1. Experience accumulated in underground ore mining is applied to solving the problem of hydromixture transportation.

2. Parameters of efficient hydromixture haul under the force mode are determined by simulating according to the criteria of transportation length and reliability.

3. Consideration of combined mining peculiarities as to changing the quality and quantity of hydromixtures fed under the force mode to achieve the length exceeding that of the traditional technology increases the efficiency of combined mining accompanied by filling voids with consolidating mixtures and leaching metals.

4. Recommendations for applying the hydromixture haul technology under the force mode can be used in underground mining of chemically extracted ores considering the environmental and economic effect.

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ТРАНСПОРТУВАННЯ ХВОСТІВ ЗБАГАЧЕННЯ І ВИЛУГОВУВАННЯ ПРИ ПІДЗЕМНІЙ РОЗРОБЦІ МЕТАЛЕВИХ РОДОВИЩ

В. Голик, М. Міцик, В. Моркун, Н. Моркун, В. Тронь

Мета. Обґрунтування раціональних параметрів ресурсозберігаючих технологічних процесів, що забезпечують оптимальні за еколого-економічними критеріями показники транспортування бетонних сумішей у режимі примусу і динаміки змінення параметрів переміщуваної маси у залежності від умов транспортування.

Методика. Комплексний метод досліджень включає узагальнення й аналіз теорії та практики транспортування сумішей, теоретичні й виробничі дослідження процесів доставки сумішей на далеку відстань, інженерне прогнозування, математичне моделювання процесів із використанням альтернативних варіантів розрахунків для розробки рекомендацій.

Результати. Деталізовано розрахунок параметрів транспортування хвостів збагачення і вилуговування у примусовому режимі роботи вібропроводу в умовах довжини доставки, що перевищує можливості самопливу. Дано розрахункові схеми визначення втрат напору та критичної швидкості потоку гідросуміші альтернативними методами з ранжируванням за ступенем надійності.

Наукова новизна. Сформульована основа нового методу управління показниками приготування та транспортування сумішей при комбінованій розробці родовищ шляхом зміни напору і швидкості подачі сумішей.

Практична значимість. Результати вирішення проблеми транспортування гідросумішей у режимі примусу шляхом спільного використання накопиченого виробничого досвіду та моделюванням процесів доставки для умов комбінованої розробки родовищ дозволяють одержати комплексний еколого-економічний ефект.

Ключові слова: *родовище, гідросуміш, транспортування, трубопровід, руда, моделювання, вібрація*

ТРАНСПОРТИРОВАНИЕ ХВОСТОВ ОБОГАЩЕНИЯ И ВЫЩЕЛАЧИВАНИЯ ПРИ ПОДЗЕМНОЙ РАЗРАБОТКЕ МЕТАЛЛИЧЕСКИХ МЕСТОРОЖДЕНИЙ

В. Голик, М. Мицик, В. Моркун, Н. Моркун, В. Тронь

Цель. Обоснование рациональных параметров ресурсосберегающих технологических процессов, обеспечивающих оптимальные по эколого-экономическим критериям показатели транспортирования бетонных смесей в режиме принуждения и динамики изменения параметров перемещаемой массы в зависимости от условий транспортирования.

Методика. Комплексный метод исследований включает обобщение и анализ теории и практики транспортирования смесей, теоретические и производственные исследования процессов доставки смесей на дальнее расстояние, инженерное прогнозирование, математическое моделирование процессов с использованием альтернативных вариантов расчетов для разработки рекомендаций.

Результаты. Детализирован расчет параметров транспортирования хвостов обогащения и выщелачивания в принудительном режиме работы вибропровода в условиях длины доставки, превышающей возможности самотека. Даны расчетные схемы определения потерь напора и критической скорости потока гидросмеси альтернативными методами с ранжированием по степени надежности.

Научная новизна. Сформулирована основа нового метода управления показателями приготовления и транспортирования смесей при комбинированной разработке месторождений путем изменения напора и скорости подачи смесей.

Практическая значимость. Результаты решения проблемы транспортирования гидросмесей в режиме принуждения путем совместного использования накопленного производственного опыта и моделированием процессов доставки для условий комбинированной разработки месторождений позволяют получить комплексный эколого-экономический эффект.

Ключевые слова: *месторождение, гидросмесь, транспортирование, трубопровод, руда, моделирование, вибрация*

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