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Methods of intensification of pipeline transportation of hydraulic mixtures when backfilling mined-out spaces

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Abstract

The paper presents an analysis of the advantages and limitations of additional measures to intensify the transportation of the backfill hydraulic mixture flow. The results of the analysis of the conditions for using pumping equipment to move flows with different rheological properties are shown. Generalizations of the methods for influencing the internal resistance of backfill hydraulic mixtures by means of mechanical activation, as well as increasing fluidity due to the use of chemical additives are given. The article presents the results of studies confirming the feasibility of using pipes with polymer lining, which has proven its efficiency in pumping flows of hydraulic mixtures with different filler concentrations. An analytical model of hydraulic mixture movement in the pipeline of the stowage complex has been developed. The trends in pressure change required to ensure the movement of hydraulic mixture in pipelines of different diameters are exponential, provided that the flow properties are constant. The effect of particle size on the motion mode of the formed heterogeneous flow, as well as on the distribution of flow density over the cross-section, characterizing the stratification and change in the rheological properties of the backfill hydraulic mixture, is assessed. An analytical model of centralized migration of the dispersed phase of the hydraulic mixture flow is formulated, describing the effect of turbulent mixing of the flow on the behavior of solid particles. An assessment of the secondary dispersion of the solid fraction of the hydraulic mixture, which causes a change in the consistency of the flow, was performed. The studies of the influence of the coefficient of consistency of the flow revealed that overgrinding of the fractions of the filler of the hydraulic mixture contributes to an increase in the required pressure in the pipeline system.

Keywords

mined out space filling; pipeline transport; pressure; auxiliary equipment; heterogeneous flow; rheological characteristics; consistency

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Introduction

In the mining industry, hydrotransport is an integral part of production processes, carrying out the pumping of ore concentrates, enrichment hosts, and backfill materials. The increase in volumes and distances of transportation of small-fraction materials makes the use of hydrotransport economically advantageous [1].

Modern development of mining enterprises is characterized by increasing scale of production and intensive extraction of minerals, accompanied by the involvement of more remote areas of deposits in the development [2]. This requires improvement of applied engineering and technical solutions for efficient and safe mining operations [3]. Chamber and continuous layer mining systems with backfilling by hardening mixtures have become the most widespread in mining enterprises due to their versatility. They are implemented when developing ore deposits of virtually any thickness and angle of incidence [4, 5]. Systems of development in a descending order impose increased requirements on the formed backfill massifs, as evidenced by expert examinations of cases of mass collapses of underworked ore and backfill massifs, the main reason for which is insufficient completeness of the backfill of the mined-out space [6]. Thus, at the Orlovsky mine, the use of a system for developing descending horizontal layers with a hardening backfill, the properties of which did not meet regulatory requirements, led to the collapse of the artificial roof in 1997 to the height of three overlying layers across the entire width of the stope. At the Maleevsky mine, when developing ore reserves using a sublevel-chamber system with continuous extraction, due to stratification of the material and insufficient strength of the formed artificial massif, a collapse of the vertical outcrop of the backfill massif occurred in 2014 [7].

Rock pressure management is one of the decisive factors for the safe and stable operation of a mining enterprise, in addition to maintaining a stable state of the rock massif, allowing for a reduction in the loss of minerals. For example, increasing the completeness of extraction of explored geological reserves of uranium ores is of great importance for the development of nuclear energy due to the limited nature of these resources, reducing the loss of raw materials during the development of deposits [8, 9]. The use of hardening backfill also reduces the risk of flooding of deposits as a result of breakthroughs of aquifers through cracks of natural and man-made origin. Insufficient justification of the physical and mechanical properties of the backfill mixture and the formed underfill led to breakthroughs of underground waters in the workings, flooding of two mines at the Verkhnekamskoye potassium-magnesium salt deposit [10]. The use of enrichment tailings, waste rock and production waste as fillers of backfill mixtures ensures effective protection of the environment from man-made pollution.

Methods and technologies

The efficiency of hydrotransportation of heterogeneous flows over long distances depends to a large extent on the cross-sectional area of the pipeline, the properties of its working surface, and the number of local resistances on horizontal and inclined sections [11-13]. The need to backfill remote sections of deposits is faced with the limited technological level of backfilling complexes, the equipment of which is often incapable of delivering hydraulic mixture to the workings. This necessitates the search for promising methods of intensifying the supply of backfilling hydraulic mixtures to remote storage and disposal areas.

To increase the range of pipeline transportation, various methods and technologies are used (Fig.1).

The use of pumping equipment is one of the main technological solutions for ensuring a pressure level throughout the entire route of transportation of the hydraulic mixture, sufficient to overcome frictional resistance in the pipeline.

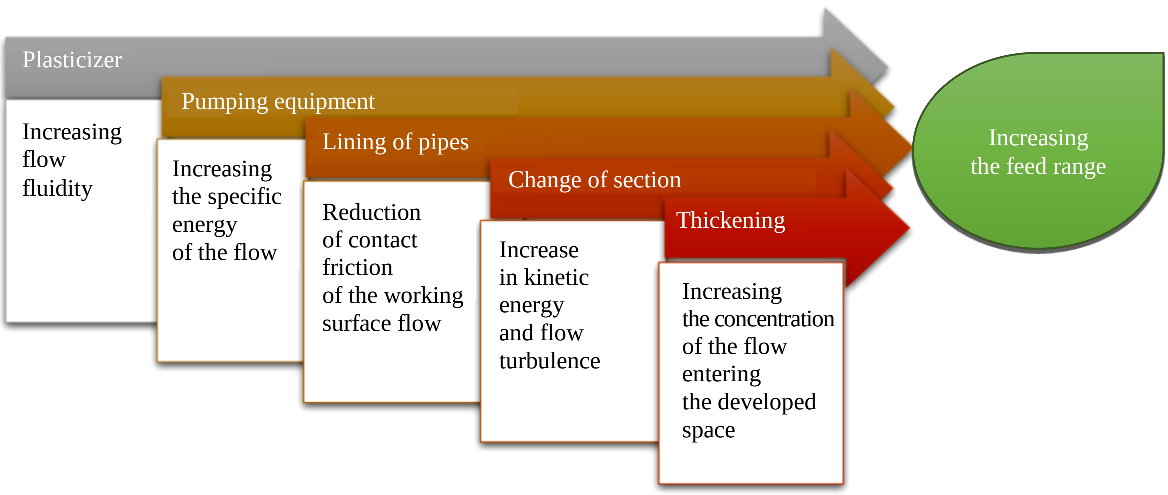

Fig.1. Methods for increasing the delivery range of hydraulic mixture

Modern requirements for ground pumps as mining and processing equipment are reduced to the ability to provide a given pressure and productivity with low energy consumption [14]. The most popular are centrifugal ground pumps that pump materials of medium and high abrasiveness. Thus, Warman AH series pumps are designed for heavy-duty operating conditions, continuous pumping of highly abrasive hydraulic mixtures of increased density. Metso Minerals X series slurry pumps are designed for heavy-duty operating conditions. Pumps of the type GraA, GrT, etc., manufactured by the Bobruisk Machine-Building Plant, are designed for pumping abrasive hydraulic mixtures with a density of up to 1800 kg/m^3. The company PGMK (Petrozavodsk) produces soil pumps for pumping abrasive hydraulic mixtures with a capacity of at least 12,000 m^3/h. Habermann pumps of the NP series are used for highly abrasive sludge and sand particles, and KB for pumping large particles, including gravel.

Increasing the filler content in the hydraulic fluid flow leads to an increase in shear resistance and necessitates a transition from centrifugal pumps to volumetric pumps. Piston pumps are used to feed pasty backfill materials characterized by high resistance to movement, for example, Putzmeister HSP series pumps with plate valves designed to provide high pressure. The results of research on the creation of magnetic peristaltic pumping units are known, in the working chamber of which, under the influence of an electromagnetic field, directed deformation waves are created that move the hydraulic mixture.

A significant drawback of pumping equipment is its low reliability. Experience shows that pumping flows with a high content of small abrasive fractions leads to rapid hydroabrasive wear of impellers and valves, which is the cause of up to 80 % of equipment accidents and failures [15].

High productivity and efficiency of transportation of hardening materials over long distances largely depends on the application of activation factors to the hydraulic mixture. At the stage of preparation of backfill mixtures, various continuous and cyclic action activators-mixers are used [16]. Roller activators of continuous or cyclic action of the system ensure effective mixing and destruction of internal bonds of the mixture components. This helps to improve the rheological properties of hardening mixtures, reduce cement consumption, and increase the strength of the massif [17].

Hydrodynamic activators with an electric drive reduce the viscosity and increase the fluidity due to mechanical disturbances in the flow of the hydraulic mixture, and contribute to an increase in the distance of stable transportation of hydraulic mixtures in stowage complexes [18]. Additional turbulent intra-flow activation due to impact interaction allows the surfaces of binder particles to be freed from oxide formations, destroying the colloidal film and promoting intensive gelation. This significantly increases the activity of the binder component and allows obtaining a homogeneous mixture with high mobility.

When transporting backfill hydraulic mixture over distances exceeding the limit of gravity transport, pneumatic transport has become widespread. It consists of supplying compressed air to the pipeline at the end of the gravity section, which helps to eliminate backfilling of pipelines. With excess air supply, the outgoing flow of hydraulic mixture is extremely uneven, which reduces the strength of the backfill mass and leads to uneven wear of the pipeline walls [19].

Vibratory gravity transport has proven itself to be a good option for increasing the range of transportation of hydraulic mixtures over long distances. It helps to reduce the resistance of the mixture movement by increasing the gradient of transverse deformations of the flow. Additionally, the strength of the formed artificial massif is increased due to the accompanying activation of the binder in the pipeline [20]. Liquefaction of the wall layer of the flow is effectively implemented with rational frequency and amplitude of pulses, as well as the correct angle of their transmission. In this case, it is necessary to take into account the average weighted size of the dispersed phase of the hydraulic mixture, as well as its concentration.

Many enterprises use low-concentration hydraulic mixtures for filling. With the simplicity of flow formation, this requires significant water consumption, as well as the use of large-diameter pipes [21].

Stabilization of the backfill mass can be achieved only by using hydraulic mixtures with a high filler content, such as enrichment tailings, sludge, and construction dispersed mixtures. Experimental studies conducted at the Scientific Center for Geomechanics and Subsoil Use Problems of the Mining University have revealed that water separation from the formed mass is reduced by more than 40 % when the concentration of the backfill mixture increases from 10 to 50 %.

Currently, the use of highly concentrated backfill mixture (paste) is becoming the most promising [22]. The concentration of solid particles in the hydraulic mixture affects its structural viscosity and resistance to flow movement; the higher it is, the more energy is required to transport the hydraulic mixture through a pipeline. To reduce energy costs for flow transportation and the environmental consequences of flooding of workings, the hydraulic mixture is thickened after enrichment [23, 24]. There are various designs of thickeners used for dewatering of backfill hydraulic mixtures. Their operating principle is based on the use of gravitational or centrifugal forces to separate the carrier medium, such as in hydrocyclones, arc and conical sieves [25, 26]. The Mining University has developed an original design of an inertial thickener that allows forming a flow of thickened backfill mixture with a concentration of up to 70 % immediately before the filled working. The high permissible flow rate of the hydraulic mixture at the inlet to the thickener working chamber allows it to be integrated into the pipeline system without the use of loops. The implementation of the thickening mechanism due to the action of a set of volumetric forces in the flow eliminates the need for additional mechanical activation of the sedimentation process and the use of power sources.

High concentration of backfill hydraulic mixture reduces crack formation and the probability of roof collapse, increasing the safety of operations. Thickening of hydraulic mixture accelerates the process of filling the mined-out space and reduces the time it takes for the massif to gain strength [27]. Mobile complexes have been developed for thickening backfill mixtures, which are placed underground. Their use, in addition to the possibility of preparing the backfill mixture directly at the backfilled working, minimizes the need to equip surface complexes-plants with thickeners [28, 29]. The use of underground thickeners allows, by moving a low-concentration flow and thickening it at the end of the transport line, to increase the range of the hydraulic mixture supply and organize the controlled removal of the recycled liquid used for production needs [30].

In addition to placing thickening equipment, mobile systems are used to increase the completeness of filling and control the quality of filling the mined-out space. Concrete pumps from Stroypark, SERMAC and other companies are used when filling deposits, including polymetallic ores. Shotcrete units are also used to fill voids by feeding mixtures into the space through a pipeline [27].

One of the main tasks for ensuring the required range of hydraulic mixture supply is to determine the rational consistency. Evaluation of the mineralogical and granulometric composition is necessary to prevent flow stratification and subsequent blockage of the pipeline system.

In order to improve the fluidity of the mixture and reduce friction between the pipe walls and the material being moved, antifriction, anticorrosion additives and plasticizing additives are used [31, 32]. Plasticizers are represented by a number of components, the most common of which are: technical lignosulfonate, sulfate-alcohol stillage, organosilicon liquid, finely dispersed limestone mixed with soap naphtha, clays and loams. In addition to natural plasticizers, chemical additives are used, represented by surfactants, subdivided into plasticizing, plasticizing-air-entraining and air-entraining. Gas-forming additives ensure the formation of uniformly distributed closed pores in the massif and are introduced to increase the frost resistance and water resistance of the massif (GKZh-94, PAK).

The use of various types of halogen rocks and water can also activate the reaction of mixtures with cement, which accelerates the process of strength gain. Injection of polymer solutions into the pipeline at relatively low velocities of the hydraulic mixture allows reducing pressure losses due to friction, since the polymer forms a lubricating ring at the pipe walls [31]. Given the high concentration and viscosity of the hydraulic mixture, its mixing with the polymer solution is minimal, which preserves the effect of reducing friction over a significant distance, which increases the transportation range. Plasticizers improve the quality of the constructed artificial backfill massif, reducing the hardening time, increase the strength of the constructed artificial massif, and fill the mined-out space due to better spreadability [33]. The high density of the hydraulic mixture leads to a significant increase in transportation costs, therefore the use of a plasticizing additive not only increases the transportation distance, but also reduces delivery costs.

A significant disadvantage of the technology for transporting hydraulic mixtures is the intensive hydroabrasive wear of the working surfaces of pipelines, amounting to 2.5-3.0 mm/year, reducing the service life to two years or less. Wear is accompanied by an increase in surface roughness and a significant increase in specific resistance to flow movement. The value of specific pressure losses during hydraulic transportation is determined according to the expression [34]:

$$I = \lambda \frac{v_{\text{sl}}^2}{2gD} + k_p \delta \sqrt[4]{i} \sqrt[3]{C_{\text{vol}}^2},$$

where λ – coefficient of hydraulic resistance; v_{sl} – average flow rate of hydraulic mixture, m/s; g – acceleration of gravity, m/s^2; D – internal diameter of the pipeline, m; k_p – coefficient characterizing the consistency of a heterogeneous flow; δ – thickness of the wall (laminar) layer, m; i – hydraulic slope, m/m; C_{vol} – volumetric concentration of hydraulic mixture, fractional units.

Wear of the working surface of pipes is caused by contact friction of solid particles against the walls and represents the loss of material as a result of repeated dynamic impact of small solid particles. The intensity and nature of wear of the pipeline surface depends on the flow parameters and the transportation mode [35]. Under the action of gravity, the transported solid particles are unevenly distributed in the pipeline cross-section and, at a flow rate below the critical value, are moved by dragging along the bottom of the pipe. When the flow rate reaches critical values, the wear of the working surface is caused by the process of impact action of the abrasive.

The desire to minimize the listed processes determines the intensive development of one of the priority areas for improving the operational characteristics of transport pipelines – the use of linings of the inner surface. In the mining industry, materials specially designed to protect against abrasive wear, chemical effects and high temperatures are often used for lining pipelines. The use of linings made of wear-resistant materials allows for a reduction in the negative impact of solid particles on the wearing surface, a reduction in friction pressure losses, and an increase in the service life of pipes [36-38].

The most widely used lining materials for pipes are ceramic, synthetic, metallic and combined coatings. Ceramic materials such as aluminum oxide or silicon carbide are produced by pressing blanks at a pressure of over 200 MPa and sintering at high temperatures. They have high resistance to abrasive wear and chemical attack and are widely used for lining pipelines in areas with high wear, such as separators, bends, diffusers or elbows. The application of a metal lining of steel plates or special alloys to the working surface is used for pipelines exposed to high temperatures and abrasive wear. Cladding by applying a lining of a lower-quality material to the working surface of a pipe made of a more wear-resistant material is used in systems where the environment is chemically aggressive.

One of the most promising lining methods is the application of polymer coatings to the inner surface of pipes. Elastomeric materials such as rubber and polyurethane implement the mechanism of elastic interaction of the dispersed phase of the flow with the working surface, providing resistance to impact wear and abrasion. Polymeric materials such as polyethylene, fluoroplastics, etc., have high chemical resistance and a low coefficient of friction [35]. Experimental studies conducted at the Department of Transport and Technological Processes and Machines of the Mining University have shown that in the case of applying a polyurethane coating to the working surface (for example, SKU-7L – a synthetic elastomer with high resistance to impact loads), the surface roughness is reduced by more than 10 times. This made it possible to reduce the coefficient of hydraulic resistance by half during the running-in period of the pipeline when transporting a hydraulic mixture prepared using iron ore enrichment tailings (Fig.2).

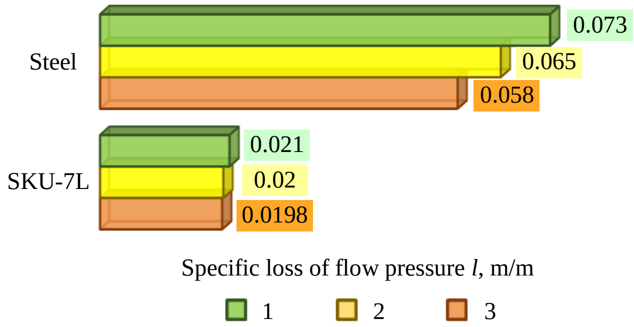

Fig.2. Comparison of specific pressure losses in pipelines with different materials of working surfaces

1 – C_{vol} = 30 %; 2 – 20 %; 3 – 10 %

Some lining compositions are a combination of different materials, such as ceramic coatings based on polymers or metal inserts in elastomer materials, which allows achieving a high level of protection of the working surface. The choice of a specific lining material depends on the operating conditions, the type of materials transported, the requirements for wear resistance and chemical resistance, as well as the project budget.

Analytical model of hydraulic fluid movement

When the backfill hydraulic mixture enters the vertical pipeline, hydrostatic pressure arises, the value of which is determined according to the expression

$$P_v = H\rho_{sl} g - \left(i_v - \frac{\rho_{sol}}{\rho_w} \right),$$

where H – height of the column of hydraulic mixture, m; ρ_{sl} – density of hydraulic mixture, kg/m^3; i_v – specific pressure losses during transportation in a vertical section of a pipeline; ρ_{sol} – density of solid fraction of filler, kg/m^3; ρ_w – density of carrier liquid, kg/m^3; the sign "–" indicates a downward direction of flow.

The flow in a vertical pipe is axisymmetric and in calculations the relative coefficient of hydraulic resistance λ is taken to be equal to one.

Under the action of this pressure, the mixture moves along an articulated horizontal or gently sloping section to the stage of equilibration with the total hydraulic losses in this section determined according to the expression [38]:

$$i_n = i'' - \left(1 + \bar{\rho}_{sol} C_{vol} / 1 + C_{vol}\right) \sin\varphi,$$

where i'' – specific pressure losses due to friction on a horizontal or slightly inclined section of a pipeline; $\bar{\rho}_{sol}$ – dimensionless density of solid phase particles; φ – angle of inclination of a pipeline section to the horizontal plane.

The efficiency of hydrotransportation is ensured by the correct choice of the pipeline diameter, which determines the level of kinetic energy during flow movement. Providing the required critical speed of movement of the hydraulic mixture allows achieving movement in a turbulent mode and rationalizing the energy consumption of the additional equipment used. Movement of filler particles in a suspended state under these conditions helps to reduce the resistance to flow movement even with an increase in concentration, which allows increasing the range of hydraulic mixture supply.

To assess the effect of diameter reduction on the transport parameters under flow continuity conditions, the Bernoulli equation is applicable:

$$\frac{v_{\text{sl1}}^2}{2g}+\frac{P_1}{g\rho_{\text{sl}}}+h_1=\frac{v_{\text{sl2}}^2}{2g}+\frac{P_2}{g\rho_{\text{sl}}}+h_2+\sum i_n L_{dt},$$

where $\sum i_n L_{dt}$ – the amount of pressure loss between the considered sections of the pipeline section L during the passage time dt of the hydraulic mixture with a specific gravity $g\rho_{\text{sl}}$.

The presence of solid particles in the flow significantly changes the distribution pattern of average longitudinal velocities in comparison with a single-phase flow, the diagrams of which in pipes with constant roughness are unchanged regardless of the diameter or direction of the flow. The determined level of critical velocity in this case must take into account the condition of equality of tangential stresses in the lower part of the pipe during the flow of the hydraulic mixture and the intensity of the friction force of solid particles on the wall. It should be noted that the initial shear stresses depend to a large extent on the time the flow is at rest. The mathematical description of the motion of two-phase flows is based on the laws of conservation of mass and momentum of energy applied to each of the flow zones: the working surface of the pipeline, the laminar film of the flow directly in contact with the pipe wall, and the core of the flow.

The solution to the problem of moving a two-phase flow in a cylindrical frame of reference with known initial and boundary conditions is formulated in the interpretation of mass exchange – the law of conservation of mass:

$$\frac{dF}{dt}+V\nabla F=0,$$

where V – velocity vector of a two-phase medium; F – vector of volumetric forces;
hydrodynamics – the law of conservation of momentum:

$$\frac{d\rho V}{dt}+\nabla\left(\rho_{\text{sl}}V^2\right)=-\nabla p+\nabla(\tau)+\rho_{\text{sl}}g;$$

τ – viscous stress tensor; p – static pressure.

To describe the conservation laws by field-type equations, each zone in the applied models is represented as a continuous medium with smoothly changing characteristics throughout the entire space. This can only be achieved with complete flow symmetry, which is unrealistic under conditions of variable speed of movement of the hydraulic mixture and significant pressure losses.

Studies of the movement of tail pulp hydraulic mixture on a linear section made it possible to estimate the change in pressure for moving a flow with a constant consistency (m = 1.4) in pipelines of different diameters (Fig.3).

According to the obtained results, the change in hydrostatic pressure depending on the flow diameter is described by the dependence

$$D=-0.67\ln\left(P_{\text{v}}\right)+2.4.$$

It is noted that a 10 % decrease in the diameter of a horizontal section of a pipeline is accompanied by an average 9 % increase in

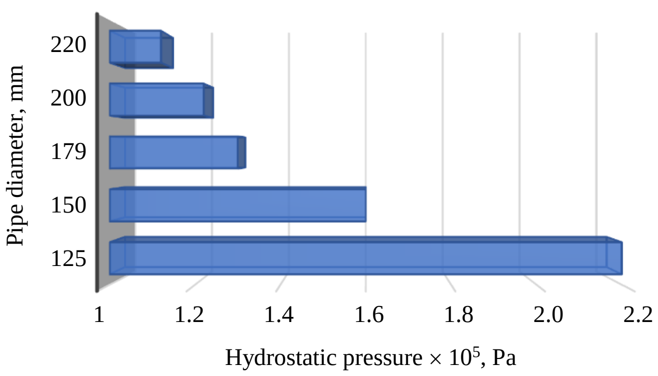

Fig.3. Change in pressure required to move the flow of hydraulic mixture, depending on the pipeline diameter

pressure. However, when the diameter reaches 180 mm and then decreases, the growth of pressure values required to ensure delivery to a given distance increase exponentially. When the diameter decreases to 150 mm, the pressure increases immediately by 26 %, and at 125 mm – by another 54 %. This trend is consistent with the dynamics of the manifestation of dilatant properties of the flow.

The implementation of a step-by-step reduction in the diameter of pipes is carried out in order to maintain the flow velocity pressure and the level of permissible pressure losses. When the cross-section is reduced by half from 50 to 25 mm, the speed increases by 4.6 times – from 2.4 to 10 m/s. The flow moves in a developed turbulent mode. Reducing the pipeline cross-section to reduce metal consumption is accompanied by a decrease in the thickness of the pipeline wall.

The flow of heterogeneous flows is characterized by the participation of dispersed fractions in turbulent mixing. The particle size determines the mechanism for implementing the rheological law of flow movement, pulsation characteristics, and particle retention conditions [39, 40]. Increasing flow saturation promotes intensification of turbulent mixing, which increases the suspension-bearing capacity of the flow. The use of fine-fraction particles (0.044-0.074 mm) as a filler due to the formation of a structural flow allows for a reduction in binder consumption, while a decrease in hydraulic resistance by 6-10 % is observed. The physical model of the flow of finely dispersed and small-fraction mixtures is described by the dependence [41]:

$$i_{\mathrm{sl}} = \lambda_{\mathrm{g}} \frac{\rho_{\mathrm{w}} v_{\mathrm{sl}}^2}{2gD},$$

where i_{sl} – specific hydraulic resistance to flow movement, Pa; ρ_{w} – density of carrier liquid, kg/m^3.

Transportation of hydraulic mixtures with coarse-grained filler is accompanied by pronounced phase slip, i.e., the dispersed phase lags behind the carrier medium, leading to stratification [42]. An increase in the filler content inevitably leads to a significant increase in the resistance to movement along the pipeline due to the formation of local zones of high concentration in the flow [43]. Transportation of such hydraulic mixtures requires high operating speeds that maintain suspended movement of particles, which is accompanied by high wear of the pipeline system and significant specific energy losses [35]. Otherwise, solid particles fall into the lower layers of the transported mixture, the flow stratifies, and transitions to an unstable state of silting. The pressure loss of the flow of a polyfractional mixture is determined according to the expression

$$i_{\mathrm{h}} = i_{\mathrm{h.s}} + \Delta i,$$

where $i_{\mathrm{h.s}}$ – specific resistance determined by hydraulic size, Pa; Δi – suspended flow resistance, Pa.

The reason for the transition is the uneven distribution of flow density across the cross-section and the stable sedimentation of filler particles at the bottom of the pipe, caused by a decrease in speed below critical values (Fig.4).

The flow velocity is the main parameter determining the kinematic structure of the flow. With an increase in the velocity of the hydraulic mixture on long straight sections, a practically uniform weighing of solid particles is achieved over the cross-section of the pipe, and the hydraulic mixture acquires the properties

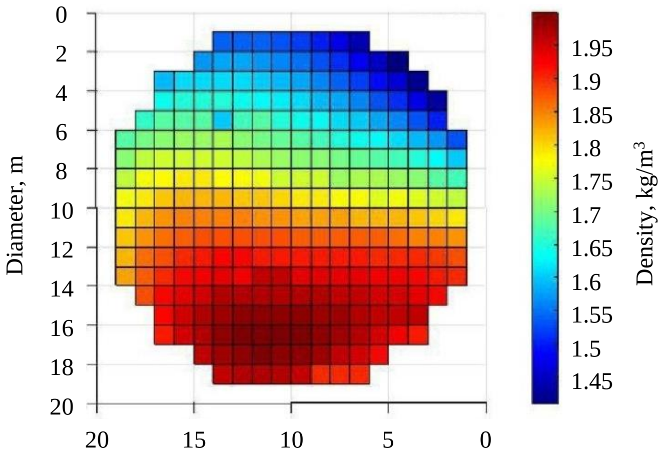

Fig.4. Distribution of hydraulic mixture concentration fields by flow cross-section during phase sliding, initial ρ_{sl} = 1700 kg/m^3

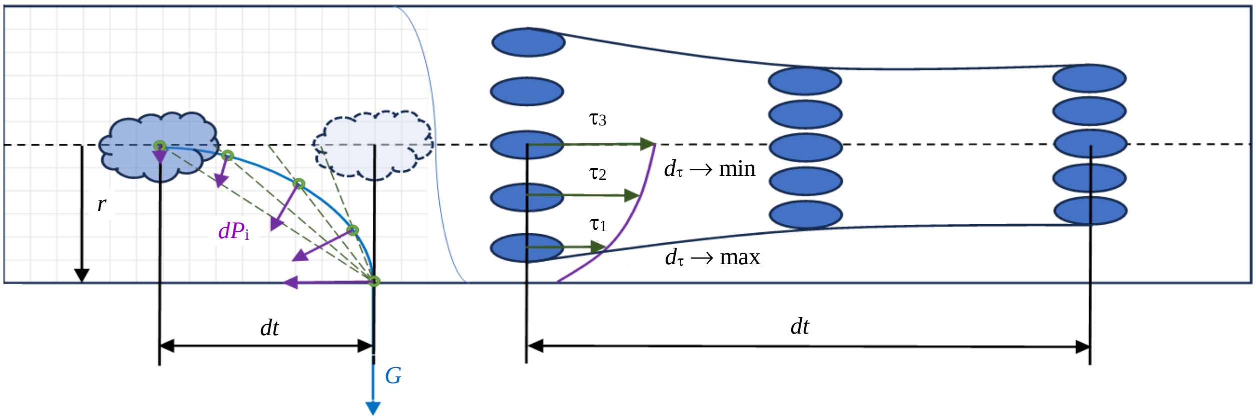

Fig.5. Migration of filler particles across the pipeline cross-section
r – flow radius; P_i – inertial force; t – time; G – weight; τ – shear stress

of a fictitious unimodal liquid of increased density. The position of the particle when moving in the flow is relative. In the external frame of reference, a change in the direction of the gravity vector (weight) G of dispersed objects will form a parabola. To assess the influence of the inertial force, it is also necessary to determine the frame of reference. Thus, an increased flow density determines a discrete consideration of the flow as a homogeneous specific volume of a given mass and the need to take into account the influence of linear acceleration. However, the influence of the heterogeneous structure also requires taking into account the turbulence of the flow determining the intensive mass exchange and forming vortex flows. This determines the consideration of the inertial force as a variable quantity dP_i, which is influenced by the radius of the flow, as well as the angular velocity of the moving vortices. This allows forming a picture of particle migration during intensive turbulent mixing of the flow. The magnitude of the resulting moment of force decreases from the flow axis to the pipe surface. Since the shear stresses $d\tau$ decrease in the direction from the pipe surface to its axis at a distance of radius r, the resulting effect will be the formation of a tendency for the particles to shift to the flow core (Fig.5).

The processes occurring in the volume of the flow during transportation over a long distance are of a probabilistic nature. The impact energy of the particles of the dispersed phase is described by the dependence [44]:

$$U = \frac{\pi \rho_{sol}}{6} \frac{v_{sl}^2}{2g} C D^2 L,$$

где ρ_{sol} – density of solid fraction of filler, kg/m^3; C – slurry concentration; L – length of pipeline section, m.

The parameters of the primary concentration and flow rate have the greatest influence on the factor of secondary grinding of the dispersed phase, since they determine the nature of the interaction of particles [45]. With intra-flow regrinding of the filler, the degree index characterizing the structural consistency of the hydraulic mixture increases [46]. This index determines a significant increase in the required pressure spent to move the flow over a given distance.

The consequence of material grinding is an increase in shear stress in the pipeline. When the hydraulic mixture moves, the generalized rheological model of Herschel – Bulkley is realized:

$$\tau = m \left(\frac{dv}{dy} \right)^n + \tau_0,$$

where m – flow consistency indicator; n – dimensionless flow behavior index, $n \geq 1$; τ_0 – initial shear stress.

As is known, effective viscosity is defined as a function of the velocity gradient and for a heterogeneous flow of hydraulic mixtures, according to the power law, increases with increasing flow velocity. The equations of conservation of mass and momentum describe the stationarity of the flow in a horizontal pipe:

$$\begin{cases} \nabla\left(A\rho_{sl}v_{sl}\right); \\ \rho_{sl}v_{sl}\nabla v = -\Delta P - f_D\dfrac{\rho}{2D}v_{sl}\left|v_{sl}\right|, \end{cases}$$

where ∇ – divergence operator characterizing the vector flow of particles through a limited cross section; ∇v – density of velocity vectors in the cross-section; A – flow cross-section, m^2; ρ_{sl} – density of hydraulic flow, kg/m^3; v_{sl} – average flow velocity, m/s; ΔP – pressure change, Pa; f_D – Darcy coefficient for flow constriction.

Taking into account the turbulent flow regime, the Darcy coefficient is determined according to the friction model described by the expression [47]:

$$\left\{ f_D = 4\left(\frac{B(n)}{\mathrm{Re}_{m.t}}\right)^{(3n+1)^{-1}} \right. ,$$

where

$$B(n) = \frac{2^{(n+4)}}{7^{7n}}\left(\frac{4n}{3n+1}\right)^{3n^2};$$

the modified Reynolds number for turbulent motion is determined according to the model:

$$\mathrm{Re}_{m.t} = \frac{6464}{(3n+1)^2}(2+n)^{\left(\frac{2+n}{1+n}\right)}.$$

The fluid behavior index allows us to characterize the ratio of the initial flow energy to the energy dissipated by the flow elements.

When designing pipeline systems that deliver hydraulic mixtures over a significant distance, it is necessary to take into account the change in the consistency of the hydraulic mixture. Secondary grinding leads to an increase in the volume concentration indicator while maintaining the mass characteristic. To assess the effect of intra-flow dispersion on the change in the specific energy of the flow, a study was carried out on the movement of the hydraulic mixture along the final section of a pipeline with a constant cross-section (Fig.6).

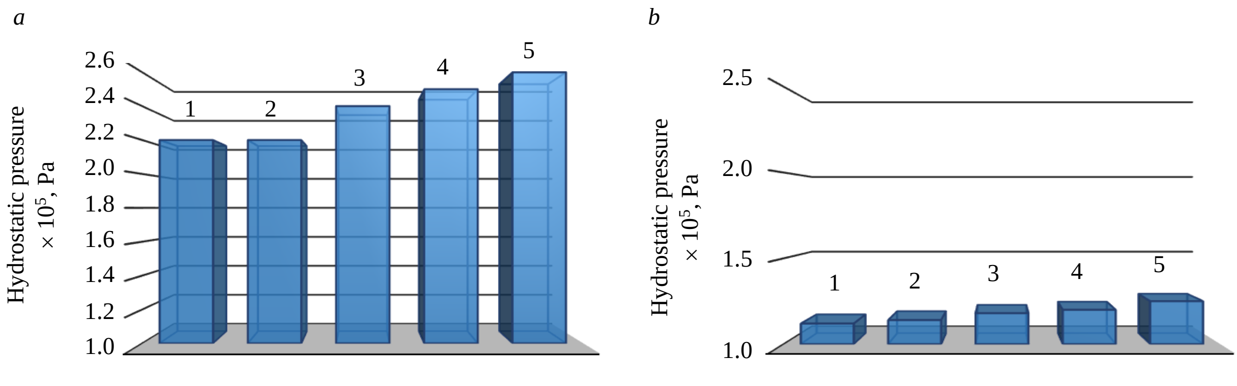

Fig.6. Change in pressure required to move the flow of hydraulic mixture, depending on its consistency:
a – D_{in} = 125 mm; *b* – D_{in} = 220 mm
1 – m = 1.4; 2 – m = 1.7; 3 – m = 2.1; 4 – m = 2.5; 5 – m = 2.9

The analysis of the results revealed that with an increase in the consistency index of the hydraulic mixture, the level of the required hydrostatic pressure increases. A twofold increase in this index leads to an increase in pressure by an average of 15 %, regardless of the pipe diameter under consideration. This will inevitably affect the change in the flow velocity, as well as its structure. Obviously, when performing hydraulic calculations, it is advisable to divide the transportation route into separate sections, taking into account the change in the rheological properties of the mixture and the value of specific losses of flow pressure.

Conclusions

Increasing the transportation distance of backfill hydraulic mixtures is faced with the difficulty of ensuring the required quality characteristics of the artificial massif due to the loss of rheological properties by the material. In conditions of a limited geodetic component of pressure, determined by the vertical section of the pipeline system of the backfill complex, the required pressure level can be ensured by using additional pumping equipment. The trend towards using hydraulic mixtures with a high filler content determines the use of pasty materials, the transportation of which is efficient due to the use of volumetric pumps – piston or peristaltic.

As the results of the study revealed, doubling the flow consistency will require increasing the pressure level in the pipeline system by 15 %, regardless of the initial diameter of the pipes. Reducing the shear stress and increasing the flow fluidity can be achieved by using plasticizers, mechanical vibration activation of the hydraulic mixture, and changing the properties of the working surface of the pipeline.

The results of the studies showed that the use of coatings and polymer linings reduces the value of the specific loss of flow pressure by more than three times, regardless of the concentration of the hydraulic mixture. However, when selecting the parameters of the system, it is necessary to take into account the physical nature of the processes realized during the movement of a two-phase flow. Maintaining the level of kinetic energy of the flow, preventing flow stratification, can be achieved by gradually reducing the diameter of the pipeline. The studies carried out have shown that this is accompanied by an exponential increase in pressure in the pipeline and promotes the migration of the filler to the core of the flow due to intensive turbulent mixing and can promote secondary dispersion of the filler.

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