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HYDRAULIC TRANSPORTATION OF THICKENED TAILINGS OF IRON ORE PROCESSING AT KACHKANARSKY GOK BASED ON RESULTS OF LABORATORY AND PILOT TESTS OF HYDROTRANSPORT SYSTEM

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The object of study is the system of hydrotransport of iron ore processing tailings at JSC «EVRAZ Kachkanarsky GOK». The aim of the work was to determine the parameters of the hydraulic transport of tailings of the iron ore enrichment at weight concentrations of the solid phase from 30 to 70 % and to develop recommendations for the industrial operation of hydraulic transport systems of highly concentrated slurries of the Tailing Facilities of the Kachkanarsky GOK. Laboratory studies of the parameters of hydrotransport of thickened tail pulps were carried out with the development of a calculation method; pilot tests of the hydrotransport system under the conditions of the Tailing Facilities of the Kachkanarsky GOK. It has been established that using polyurethane coatings on the inner surface of the slurry lines significantly (1.75 times) decrease the specific pressure loss on the hydrotransport of thickened fluids. This allows to significantly increase the range of transportation for placing tailings in the distant parts of the storage zone. The introduction of research results is in the project of reconstruction and development of the tailing facility of the TF of the Kachkanarsky GOK for the period 2018-2020. It is proposed to use the results of work in the project of reconstruction of the hydraulic transport system at the TF of the Kachkanarsky GOK by switching to the hydraulic transport of slurries thickened to weight concentrations of 35-40 % in the slurry pipes with an internal polyurethane coating, which will ensure energy saving in the hydraulic transport process.

Key words: hydrotransport; thickened slurry; tailings; pressure loss; polyurethane coatings; laboratory and pilot tests

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Introduction. One of the important directions of mining production intensification, increasing its efficiency and competitiveness in the conditions of modern market relations is the creation of a powerful transport unit capable of significantly increasing the productivity of transport systems while reducing the cost of transportation of mineral raw materials and derivative products. The development of such a base is associated with the introduction of continuous transportation, in mining the most common type of this transport is hydraulic pipeline.

At present, about 400 pipeline transport with pumps function in the mining industrial complex, the total length of pipeline exceeds 1,300 km. These systems annually move over 1.5 billion tons of various solid bulk materials, mainly processing tailings and concentrates [13].

JSC «EVRAZ KGOK» is one of the five largest mining enterprises in Russia. The production capacity of the plant is more than 55 million tons of iron ore per year. The main consumer is JSC «EVRAZ NTMK» JSC. Currently, the Kachkanarsky Mining and Processing Plant produces ore from three quarries with its further processing in crushing, enrichment, agglomeration and lumping workshops [3].

Analysis of the operation of hydrotransport systems in mining enterprises shows that the efficiency of this transport does not match its technical capabilities, the work labour input during operation is high, the abrasive wear of pipelines is heavy, the intensity of metal and power consumption of hydrotransport systems is huge too.

The specific energy consumption of hydraulic transport depends on the specific pressure loss and the concentration of the solid phase of the slurry [1]:

$$E = \frac{N}{q_\text{s} L} = \frac{\rho_\text{fl} g I_\text{fl}}{3{,}6 \rho_\text{s} c_\text{vol}},$$

Fig.1. Laboratory hydraulic transport installation

where E – specific energy intensity of the process, kW·h/(t·km); N – pump power, kW; q_s – system performance for solid materials, kg/h; L – pipeline length (transportation distance), km; ρ_{fl} – hydraulic fluid density, kg/m^3; ρ_s – density of solid tailings, kg/m^3; g – acceleration of gravity, m/s^2; I_{fl} – specific pressure loss, mCE/m; c_{vol} – volumetric concentration of solids in hydraulic fluid.

From the equation it can be seen that the energy intensity of the transportation process mainly depends on specific pressure loss and I_{fl} during transportation of the fluid (slurry tailings) through the pipeline and on concentration of the solid phase c_{vol} in the transported hydraulic fluid flow. Reduction of pressure loss and increase of concentration lead to a decrease work for pumping a given volume of solid material – tailings.

Research. Laboratory studies of slurry tailings hydrotransport of the Kachkanarsky mining and concentrating operations were carried out in the laboratory of the Department of Mining Machines at St. Petersburg Mining University. Experimental installation is shown in Fig.1. Liquid (clear water or hydraulic fluid) from a sump with a capacity of 0.5 m^3 was pumped through pipelines using a P12.5/12.5SP centrifugal pump with a capacity of 12.5 m^3/h. The solid material was taken from iron ore tailings of the Tailing Facility of the Kachkanarsky GOK, the plant gave it for testing purposes. Tails are characterized by a certain chemical composition, and their mechanical characteristics are determined by the adopted enrichment technology.

The enrichment technology for titanium-magnetite ores at Kachkanarsky GOK includes four-stage crushing, dry magnetic separation, two-stage grinding, wet magnetic separation in the third stage, and dehydration of the concentrate. The chemical composition of tailings according to the Institute of Mineralogy, Geochemistry and Crystal Chemistry of Rare Elements [4] is the following, %: silicon oxide (SiO_2) – 45.02; titanium dioxide (TiO_2) – 0.67; aluminum oxide (Al_2O_3) – 8.6; iron oxide (Fe_2O_3) – 17.7; ferrous oxide (FeO) – 3.95; manganese oxide (MnO) – 0.14; calcium oxide (CaO) – 20.8; sodium oxide (Na_2O) – 0.90; other – 2.24.

The solid particle size distribution of enrichment tails according to size class is given below:

Size class, mm	+1.6	–1.60 + 0.56	– 0.56 + 0.28	– 0.28 + 0.14	– 0.14 + 0.071	– 0.071
Content, %	3.6	25.3	23.0	20.7	14.8	12.6

The enrichment tailings given by Kachkanarksy GOK were taken from tailings beach. They have a significant proportion of coarse-grained solid particles with inclusions of metal fractions from the balls used in ball mills at the grinding stage.

According to the granulometric composition, it can be seen that the solid material is mainly represented by particle size classes –0.14 mm – 27.4 %, class –0.071 – 12.6 %. The weighted average particle diameter is

$$d_{\text{av}} = \frac{\sum_{i=1}^{n=5} P_i d_i}{100} = \frac{1.6 \cdot 3.6 + 25.3 \cdot 1.08 + 23 \cdot 0.42 + 20.7 \cdot 0.21 + 14.8 \cdot 0.105 + 0.035 \cdot 12{,}6}{100} = 0.491 \text{ mm}.$$

The histogram of the distribution of solid particles of tailings is shown in Fig.2.

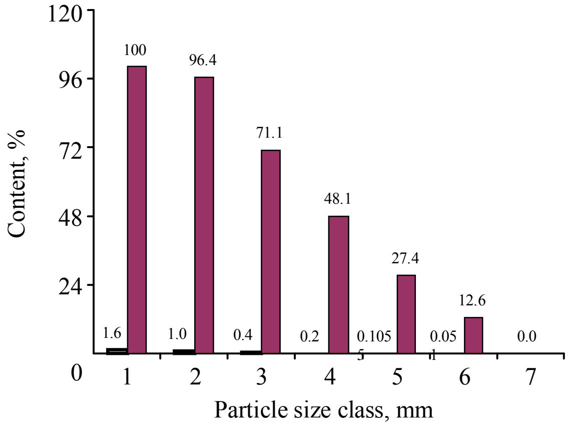

Fig.2. Histogram of solid particles distribution by size class

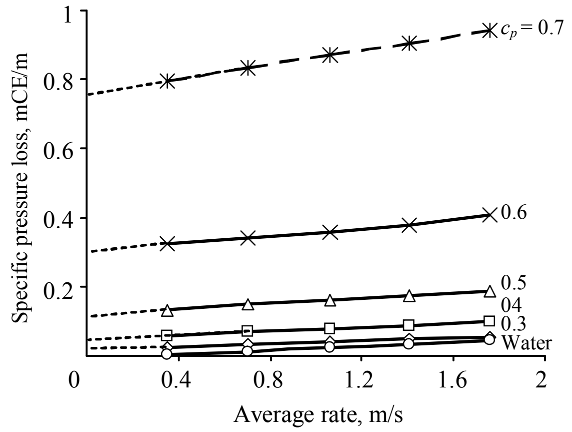

Fig.3. Diagram of dependency of pressure loss from average rate of hydraulic fluid flow, D_p = 0.05 m

Analysis of the particle size distribution was performed by sampling, filtering, drying and sieving of dry material through a standard set of sieves. The amount of material was determined by weighing the individual fractions. The accuracy of sieve analysis on a mechanical analyzer was 5 % [7].

The measured mean values of pressure losses obtained in experimental studies of the flow through a pipeline of hydraulic fluid of tailings of iron ore enrichment of four concentrations are given in Table 1. Graphic dependences of pressure loss on the average flow rate of the mixture according to laboratory experiments are shown in Fig.3.

Table 1

Experimental data on flow rate of hydraulic tailings of iron ore enrichment in pipeline (D_p = 0.05 m)

Average velocity, m/s	Weight concentration, %						
	30	40	50	60	70 (theory)	Water	Re number (water)
0.352	0.026/1075*	0.057/790	0.134/590	0.323/440	0.797/343	0.003	17300
0.704	0.033/2150	0.069/1590	0.148/1190	0.342/890	0.833/686	0.012	34600
1.06	0.041/3200	0.078/2390	0.162/1780	0.360/1340	0.87/1033	0.024	52100
1.41	0.048/4300	0.088/3180	0.175/2360	0.380/1780	0.906/1374	0.039	69320
1.76	0.056/5370	0.098/3970	0.189/2950	0.41/2230	0.94/1715	0.058	86530

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* In the numerator – the pressure loss, m, in the denominator – the Re criterion.

From Fig. 3 and Table 1, it follows that in all the studied concentrations, the slurries exhibit the properties of non-Newtonian liquids. At the bottom of the curves at flow rates of about 1 m/s and up to 0.5 m/s (for all slurries) there is a linear section indicating the laminar flow regime.

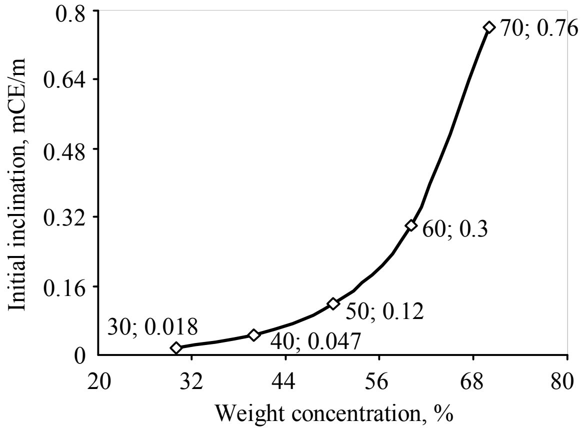

Fig.4. Changes of initial inclination of solid phase concentration of hydraulic fluid

Pressure loss grows with concentration of solid material increase, which is clearly seen in Fig.3. The inclination of the linear sections increases with rise of volume concentration. The dashed lines drawn in the continuation of the linear sections of the curves from the point of minimum average flow rate of the mixture, mark on the axis of pressure loss ordinates corresponding to the initial slope i_0. The values of the initial slope increase with concentration growth (Fig.4).

The initial hydraulic inclination indicates the non-Newtonian nature of the fluid flow. For concentrated iron ore slurry tailings, the solid phase of which mainly contains particles of relatively small classes (d_o = 0.491 mm with a predominant class of –0.044 to 80%), is characterized by the formation of an internal structure due to adhesion forces and coagulation of individual particles distributed in a continuous liquid environment.

The initial pressure loss is the result of the sum of resistances from the adhesion forces between the particles and the friction forces between them, i.e.

$$i_0 = i_p + i_f\,,$$

where i_0 – initial inclination; i_p – a part of initial inclination due to adhesion forces between particles; i_f – a part of initial inclination due to friction forces between particles.

The curve of Fig. 4 is described by the formula

$$i_0 = \frac{0{,}496 \cdot 10^{4{,}525 \cdot c_p}}{\rho_{\text{fl}} g D}\,.$$

The initial inclination, as follows from the above formula, depends on the concentration of solid particles of enrichment tailings and the diameter of the pipeline. Table 2 shows the calculated values of the initial inclination for various concentrations and pipe diameters.

Table 2

Calculated values of initial inclination

Weight concentration c_p	Initial inclination, mCE/m for a given pipe diameter, m					
	0.05	0.1	0.2	0.4	0.5	1.0
0.3	0.0182	0.009	0.004	0.002	0.0018	0.001
0.4	0.048	0.024	0.012	0.006	0.005	0.002
0.5	0.121	0.06	0.03	0.015	0.012	0.006
0.6	0.305	0.153	0.076	0.038	0.03	0.015
0.7	0.761	0.381	0.19	0.095	0.076	0.038

From Table 2 it can be seen that with increasing concentration of solid particles, the initial inclination grows, and with increasing diameter of the pipeline it decreases. When starting the pumping system of the hydrotransport system, it is necessary that the developed pressure is greater than the initial inclination.

Analysis of the experimental dependences of specific pressure losses on the average flow rate of the slurry shows that slurries in the mass concentration range from 30 to 60% are non-Newtonian fluids, the flow of which is described by the Bingham – Shvedov equation [11, 12]. Due to the high concentration values, the flow regime in the pipeline is D = 50 mm in almost all concentrations is laminar and transitional to turbulent mode. The general equation for pressure loss can be written as:

$$i_{\text{m/m}} = \frac{4\left(\tau_0 + \eta_{\text{ef}}\frac{8v}{D}\right)}{\rho_{\text{fl}} g D},$$

where τ_0 – initial shearing force, Pa; η_{ef} – dynamic coefficient of effective viscosity, Pa·s; v – average rate of hydraulic fluid, m/s; D – pipe diameter, m; ρ_{fl} – fluid density, kg/m^3; g – acceleration of gravity, m/s^2.

The results of laboratory studies make it possible to preliminarily estimate the magnitude of pressure losses in pipelines of a different diameter, for example, in an industrial pipeline with a diameter $DN1000$, using the method of the similarity theory for hydrodynamic processes [5].

In accordance with the second similarity theorem for such processes, the differential equations of motion can be replaced by an equation of similarity numbers:

$$f(K_1, K_2, K_3, \ldots) = 0\,,$$

where K_i – similarity numbers.

For the case of the similarity of hydrodynamic fluid flows, this function has the form

$$f(\mathrm{Eu}, \mathrm{Re}, \mathrm{Fr}) = 0\,,$$

where Eu – Euler number (ration of pressure force to inertia); Re – Reynolds number (ratio of inertia forces to viscosity forces); Fr – Froude number (ratio of inertial forces to gravity).

The last equation can be written as follows

$$A\left(\mathrm{Eu}^n\,\mathrm{Re}^m\,\mathrm{Fr}^q\right) = 0\,.$$

In this equation there are determined and determining numbers of similarity. The determined similarity number is the Euler number, since it contains the desired value of pressure loss. In this regard, we can rewrite the last equality:

$$\mathrm{Eu} = A\left(\mathrm{Re}^m\,\mathrm{Fr}^q\, i_L\right),$$

where $i_L = L/D$ – invariant of geometric similarity.

In these equations, the number Fr with flow in horizontal pipes is not significant and can be neglected. Then, in the final form, the similarity equation for the flow of fluids in horizontal pipes will be:

$$\mathrm{Eu} = A\left(\mathrm{Re}^m\, i_L\right).$$

In hydrodynamics, a similarity equation is known for the horizontal flow of a viscous Newtonian fluid

$$\mathrm{Eu} = k\,\mathrm{Re}^{-0.25}\left(\frac{L}{D}\right),$$

where coefficient $k = 0.158$ [5].

For non-Newtonian liquids, which include thickened slurry tailings, it is necessary to determine the value of this coefficient.

We transform the resulting similarity equation by writing the value of the Euler number to be determined

$$\frac{\Delta P}{\rho_{\mathrm{fl}} v^2} = k\,\mathrm{Re}^{-0.25}\left(\frac{L}{D}\right) \to \frac{\rho_{\mathrm{fl}} g h}{\rho_{\mathrm{fl}} v^2 L} = k\,\frac{\mathrm{Re}^{-0.25}}{D} \to \frac{h}{L} = k\,\frac{\rho_{\mathrm{fl}} v^2\,\mathrm{Re}^{-0.25}}{\rho_{\mathrm{fl}} g D}.$$

As a result, we have the equality

$$i = k\,\mathrm{Re}^{-0.25}\,\frac{v^2}{gD} = 2k\,\mathrm{Re}^{-0.25}\,\frac{v^2}{2gD}\,.$$

For non-Newtonian slurries that show rheological properties, and described by the Bingham – Shvedov equation, the pressure loss is proportional to the coefficient $\dfrac{\lambda}{(1-\sigma)k_{\mathrm{st}}}$. Therefore, we can equate

$$2k\,\mathrm{Re}^{-0.25} = \frac{\lambda}{(1-\sigma)k_{\mathrm{st}}}\,,$$

and we have

$$k = \frac{\lambda}{2(1-\sigma)k_{\mathrm{st}}\,\mathrm{Re}^{-0.25}}\,,$$

where $\sigma = \tau/\tau_0$ – specific shear stress; k_{st} – structure coefficient.

It can be seen from the formula that the value of the coefficient *k* depends on the concentration of the solid phase, since the relative shear stress and the coefficient of the structure are functions of this characteristic of the slurry.

Let us determine the value of *k*, taking into account the known rheological characteristics of slurries [6, 10]:

$$c_p = 30\,\%;\ \sigma = \frac{\tau_0}{\tau_0 + \eta_{\text{ef}}\dot{\gamma}};\quad \tau_0 = 0.124 \cdot 10^{4.525 \cdot c_{\text{з}}} = 0.124 \cdot 10^{4.525 \cdot 0.3} = 2.82\,\text{Pa};$$

$$\eta_{\text{ef}} = 6{,}31 \cdot 10^{1.72 \cdot c_p} = 20.7 \cdot 10^{-3}\ \text{Pa·s};\quad \dot{\gamma} = \frac{8v}{D} = \frac{8 \cdot 1.41}{0.05} = 225.6\ \text{s}^{-1};$$

$$\sigma = \frac{2.82}{2.82 + 0.0207 \cdot 225.6} = 0.376;\quad k_{\text{st}} = 1 + 3.45 c_{\text{vol}} = 1 + 3.45 \cdot 0.115 = 1.4.$$

Let us take the flow rate equal to v = 1.41 m/s (see Table 1). The Reynolds number is:

$$\text{Re} = \frac{vD\rho_{\text{fl}}}{\eta_{\text{ef}}} = \frac{1.41 \cdot 0.05 \cdot 1264}{0.0207} = 4305.$$

Take the formula Blasius

$$\lambda = \frac{0.3164}{\text{Re}^{0.25}} = 0.04,\quad k = \frac{0.04}{2 \cdot (1 - 0.376) \cdot 1.4 \cdot 4305^{-0.25}} = 0.1855.$$

The pressure loss according to formula

$$i = 0.1855 \cdot 4305^{-0.25} \frac{1.41^2}{2 \cdot 9.81 \cdot 0.05} = 0/05\ \text{mCE/m}.$$

From table 1 we find that the actual (measured) pressure loss is 0.046 mCE/m. The error of the calculated and experimental data is

$$\varepsilon = \frac{i_{\text{calc}} - i_{\text{exp}}}{i_{\text{exp}}} = \frac{0.05 - 0.046}{0.046} \cdot 100\,\% = 4.8\ \%.$$

Consequently, the developed methodology for recalculating pressure losses from one pipe diameter to another can be used for a preliminary assessment of pressure losses.

Results. A pilot plant for hydrotransport tests was mounted by the employees of PNS-I TF (Fig.5) [2, 9].

The slurry with a given concentration of solid tailings was pumped by an 8Gr-8 ground pump with a capacity of Q = 400 m^3/h. The transport line is made in the form of a loop consisting of two pipelines – steel DN200 and DN190 with internal polyurethane coating. The section of pipeline DN190 is located 3m below the steel pipeline.

Each pipeline has a measuring section with a length of L = 15 m. Spring gauges with separators for registering pressure drop are installed on measuring sections.

Fig.5. Separate elements of a pilot industrial unit for hydraulic transportation of slurry tailings

The supply tank with a volume of W = 1.7 m^3 was made of a pipe with a diameter of 1000 mm and a height of 2.5 m. The bottom of the tank was inclined towards the suction pipe. The slurry stream was sucked up by a ground pump, transported along a pipeline loop and drained into the supply tank.

A fixed mass of solid tailings was poured into the supply tank using a bridge crane. The level of slurry in the supply tank and its volume remained constant.

Weight concentration of slurry was calculated by the formula

$$c_p = \frac{M_{\text{sol}}}{M_{\text{fl}}} = \frac{M_{\text{sol}}}{M_{\text{w}} + M_{\text{sol}}},$$

where c_{p} – weight concentration of hydraulic fluid, fr. unit; M_{sol} – weight of solid tailings loaded into the supply tank, kg; M_{w} – weight of water, numerically equal to the volume of water, kg.

Before the start of the experiments, there were tests performed on pure water. At the same time, the operability of the equipment, pump, instruments (ultrasonic flow meter, pressure gauges), and tightness of the connections were checked. The installation worked on the expected nominal performance. Flow meter and gauges showed stable calculated values. The volume of fluid in the supply tank remained constant at the level of the drain hole.

The measured parameters of hydraulic transportation of tailings, obtained during pilot tests, are given in Table 3 and in Fig.6.

Table 3

Values of pressure loss according to experimental data

Concentration, fr. unit	Density, kg/m^3	Flow rate in pipes, m/s		Pressure losses in pipes, mCE/m		Resistance coefficient λ	
		Steel	Lined	Steel	Lined	Steel	Lined
7	1051	3.82	4.23	0.062	0.04	0.016	0.008
13	1100	3.88	4.3	0.088	0.06	0.021	0.011
19	1152	3.85	4.27	0.113	0.078	0.026	0.014
24	1200	3.73	4.14	0.127	0.099	0.030	0.018
29	1253	3.66	4.06	0.149	0.105	0.035	0.019
34	1310	3.54	3.92	0.163	0.124	0.039	0.023
38	1361	3.49	3.86	0.182	0.12	0.043	0.022
42	1414	3.41	3.78	0.192	0.125	0.046	0.023
45	1458	3.29	3.64	0.197	0.151	0.049	0.029
49	1517	3.15	3.49	0.199	0.148	0.052	0.03
52	1568	2.98	3.3	0.195	0.142	0.055	0.031
53	1584	2.91	3.22	0.191	0.136	0.056	0.031

The results of the experiments show that the specific pressure loss in the experimental lined DN190 pipeline is 1.4 times less than in the steel pipeline DN200. It should be noted that the lined pipeline was of a smaller diameter, which resulted in a higher flow rate of the slurry, on which the kinetic energy of the flow and, consequently, friction loss, depends. At equal diameters of pipelines, the ratio of pressure losses in steel and lined pipelines would be at least 1.75.

Let us show it on a specific conversion (Table 3).

Calculation is made according to formula

$$i = \lambda \frac{v^2}{2gD} \frac{\rho_c}{\rho_0}.$$

Take the average speed in the lined pipeline, equal to the speed in the steel pipeline,

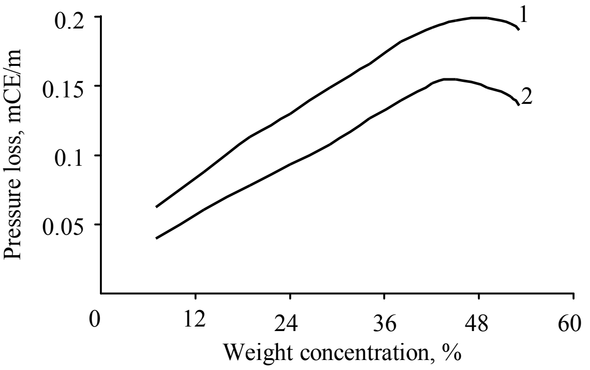

Fig.6. Pressure loss in pipes during changes of hydraulic fluid concentration

1 – steel pipe, D = 200 mm; 2 – lined pipe, D = 190 mm

$$v_{\text{st}} = v_{\text{lin}}.$$

The slurry concentration is $c_p = 49$ %.

Let us calculate the coefficient of hydraulic resistance according to the formula obtained for the lined pipeline,

$$\lambda = 0.05c_p + 0.0045 = 0.05 \cdot 0.49 + 0.0045 = 0.029.$$

This formula was obtained during processing of experimental data [3].

For concentration of 49 % the slurry density is 1517 kg/m^3, the slurry flow rate is 3.15 m/s.

The pressure loss in lined pipeline with diameter of 200 mm is

$$i = 0.029 \frac{3.15^2}{2 \cdot 9.81 \cdot 0.2} 1.517 = 0.111 \text{ m/m}.$$

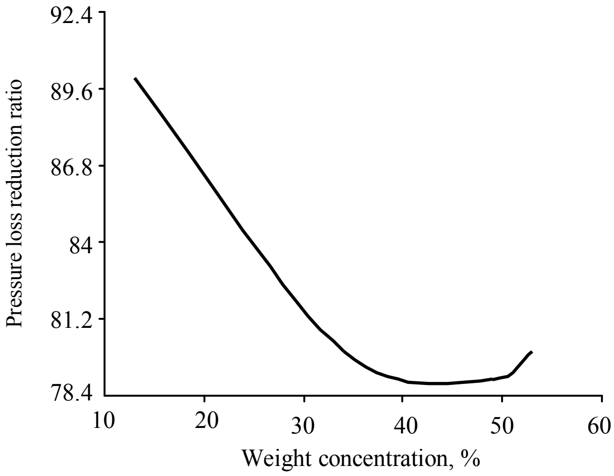

Fig.7. Pressure loss reduction ratio of slurry concentration in lined pipeline *DN*200 in relation to steel pipeline *DN*200

Relative reduction of pressure loss in lined pipeline:

$$\varepsilon = \frac{i_{\text{st}}}{i_{\text{lin}}} = \frac{0.199}{0.111} = 1.79; \quad \varepsilon_1 = \frac{i_{\text{st}} - i_{\text{lin}}}{i_{\text{lin}}} \cdot 100\% = \frac{0.199 - 0.111}{0.111} \cdot 100\% = 79\%.$$

The conversion of pressure loss values for the lined pipeline was performed when operating at other concentrations (Table 3, Fig.7). The graph in Fig.7 shows that over the entire range of concentrations of iron ore slurry tailings, the pressure loss in the lined pipe with polyurethane coating DN200 pipeline is not less than 1.75 times lower than in the steel DN200 pipeline without coating.

The results of the laboratory and pilot studies were adopted for use in the project for the reconstruction of the hydraulic transportation system of the thickened tailings of the Kachkanar mining and enrichment plant in accordance with the development plan of the tailing facilities of the ERAZ Kachkanarsky GOK.

Conclusions

1. With the existing tailings formation rate at the EVRAZ KGOK concentration plant in the amount of 4903 t/h, including section 1-15 in the amount of 2509 t/h, section 16-29 in the amount of 2394 t/h, and the accepted degree of thickening of the original slurry tailing on the designed thickening units KS-1 and KS-2 to 40% by weight, to optimize the hydraulic transportation system in the section from PNS II to the hydraulic-cloning complex, it is necessary to provide the pipes with an internal polyurethane coating.

2. The use of pipes with an internal polyurethane coating allows to supply thickened slurry for storage in the far sections of the tailings.

3. The performed analysis of the use of slurry pipes with polyurethane coating on the section for supplying thickened tailings in comparison with steel pipes shows that the economic effect is achieved already in the first 3-4 years of operation of the slurry line, and for 4-5 years of operation will ensure full payback of initial capital costs.

4. The use of steel pipes with an internal polyurethane coating reduces the electricity consumption for transportation of thickened tailings in comparison with steel pipes by an average of 22-24 %.

5. The life cycle costs for 10 years of operation of pipes with a polyurethane coating on the hydraulic transportation section for thickened tailings are two times cheaper than the operation of steel pipes without coating.

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