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THE KACHKANARSKY MCC IRON ORE PROCESSING TAILINGS SLURRY HYDRAULIC TRANSPORT PARAMETERS

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The paper describes the Kachkanarsky Mining-and-Concentrating Complex (KMCC) iron ore processing tailings slurry hydraulic transport parameters determination with solid phase mass fraction from 30 to 70% and presents the recommendations developed for commercial operation of highly-concentrated slurry hydraulic transport in the Kachkanarsky MCC tailings disposal system. The analytical methods included the laboratory studies of thickened tailings slurry hydraulic transport parameters with development of calculation methodology; pilot-scale testing of the Kachkanarsky MCC tailings hydraulic transport system. It was established, that with use of polyurethane coating on internal surface of pipelines, specific head losses are significantly reduced (by factor of 1.75) in thickened tailings slurry hydraulic transport. This permits one to considerably increase hydraulic transport distances in tailings disposal to distant areas of the tailings storage pond. The accomplished technical and economic calculations verified the economic efficiency of applying steel pipelines with internal polyurethane coating.

KEY WORDS: hydrotransport, condensed slurry, tailings, head loss, polyurethane coatings.

NOTATION

E	Specific energy for hydraulic transport (kWh/t/km)
N	Pump power (kW)
q_s	Solid materials delivery rate (kg/h)
L	Pipeline length (transportation distance) (km)
ρ_{fl}	Carrier fluid density (kg/m^3)
ρ_s	Density of solid tailings (kg/m^3)
g	Acceleration of gravity (m/s^2)
I_{fl}	Specific head loss (mH_2O/m)
c_{vol}	Volumetric concentration of solids, %
i_0	Initial slope (mH_2O/m)
i_p	Initial slope due to adhesion forces between particles
i_f	Initial slope due to friction forces between particles

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$i_{m/m}$ Specific head loss (mH_2O/m)
τ_0 Yield shear stress (Pa)
η_{ef} Effective viscosity, Pas
v Average velocity, m/s

1. 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, mining the most common type of this transport is hydraulic pipeline.

At present, about 400 pipelines with pumps function in the mining the total length of pipeline exceeds 1300 km. These systems annually move over 1.5 billion tons of various solid bulk materials, mainly processing tailings and concentrates. 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. Currently, the Kachkanarsky MCC produces ore from three quarries with its further processing in crushing, enrichment, agglomeration and lumping workshops.

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 required for hydraulic transport depends on the specific pressure loss and concentration of solid phase of the slurry Alexandrov et al (2017)

$$E = \frac{N}{q_s L} = \frac{\rho_{fl} g I_{fl}}{3.6 \rho_s c_{vol}} \quad (1)$$

From Equation 1, 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.

2. 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 Transport Machines at St. Petersburg Mining University. Experimental installation is shown in Figure 1. Liquid (clear water or slurry) 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 MCC, 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 MCC 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 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 processing tails according is presented in Figure 2. The tailings given by Kachkanarsky MCC 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. The weighted average particle diameter is 0.491 mm. The histogram of the distribution of solid particles of tailings is shown in Figure 2.

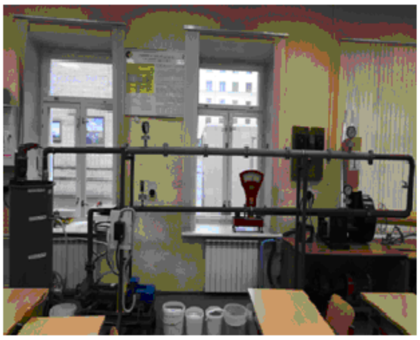

Figure 1. Laboratory installation

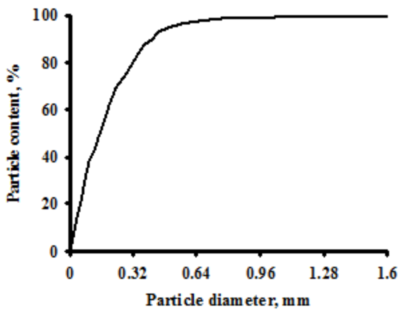

Figure 2. Particle size distribution

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 head loss measured during the flow of the mixtures through the pipeline of the laboratory installation is given in Table 1. Graphic dependences specific head loss on the average velocity of the slurry according to laboratory experiments are shown in Figure 3.

From Figure 3, it follows that in all the studied concentrations, the slurries exhibit the properties of non-Newtonian liquids. At the bottom of the curves at velocity 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. Head loss grows with concentration of solid material increase, which is seen in Figure 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 velocity of the mixture, mark on the axis of head loss ordinates corresponding to the initial slope i_0.

Table 1

Experimental data on the flow of slurry in a pipeline with a diameter of 50 mm

Average velocity, m/s	Head loss (mH_2O/m) for mass concentration,%						
	30	40	50	60	70 (estimated)	Water	Reynolds number
0.352	0.026	0.057	0.134	0.323	0.797	0.003	17300
0.704	0.033	0.069	0.148	0.342	0.833	0.012	34600
1.06	0.041	0.078	0.162	0.360	0.870	0.024	52100
1.41	0.048	0.088	0.175	0.380	0.906	0.039	69320
1.76	0.056	0.098	0.189	0.410	0.940	0.058	86530

The initial hydraulic slope 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_0 = 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 slope is the result of the sum of resistances from the adhesion forces i_p between the particles and the friction forces if between them, i.e.

$$i_0 = i_p + i_f \tag{2}$$

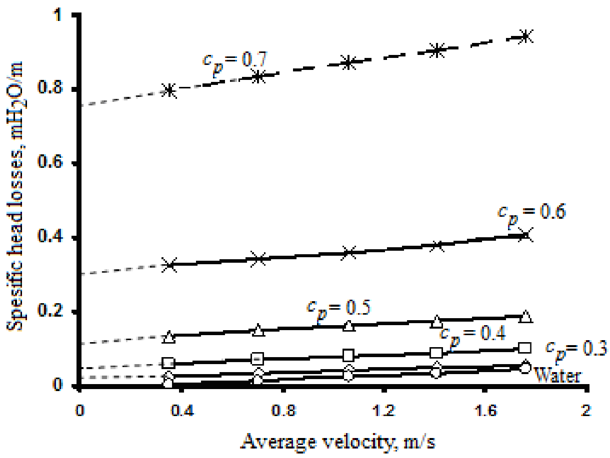

Figure 3. Diagram of dependency initial slope i_0 from velocity of mixture, D_p = 0.05 m

The initial slope depends on the concentration of solids particles of enrichment tailings and the diameter of the pipeline. Table 2 shows the calculated values of the initial slope for various concentrations and pipe diameters.

From Table 2 it can be seen that with increasing concentration of solid particles, the initial slope grows, and with increasing pipe diameter D_p it decreases. When starting the pumping system of the hydrotransport system, it is necessary that the developed pressure is greater than the initial slope. 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 equation. Due to the high concentration values, the flow regime in the pipeline is D_p = 50 mm in almost all concentrations is laminar and transitional to turbulent mode. The general equation for specific head loss can be written as:

$$i_{m/m} = \frac{4\left(\tau_0 + \eta_{ef}\frac{8v}{D_p}\right)}{\rho_{fl} g D_p} \tag{3}$$

The results of laboratory studies make it possible estimate the magnitude of pressure losses in pipelines of a different diameter, for example, in an industrial pipeline with a diameter DN1000, using the similarity theory for hydrodynamic processes, Vasilyeva and Foight (2016). In accordance with the second similarity theorem for such processes, the differential equations of motion can be replaced by an equation of similarity numbers

$$f(Eu, \mathrm{Re}, Fr) = 0 \tag{4}$$

where Eu - Euler number; Re – Reynolds number, Fr – Froude number.

Table 2

Calculated values of initial slope

Mass concentration c_p	Initial slope (mH_2O/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

The last equation can be written as follows

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

This equation has definable and defining similarity numbers. The definable similarity number is the Euler number, since it contains the desired value of pressure loss. Therefore, we can rewrite the last equality as:

$$Eu = k\,\mathrm{Re}^{-0,25}\left(\frac{L}{D_p}\right)$$

where coefficient $k = 0.158$.

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

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

As a result, we have the equality

$$i = k\,\mathrm{Re}^{-0.25} \cdot \frac{v^2}{gD_p} = 2k\,\mathrm{Re}^{-0.25} \cdot \frac{v^2}{2gD_p} \tag{5}$$

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

$$2k\,\mathrm{Re}^{-0.25} = \frac{\lambda}{(1-\sigma)k_{str}} \text{ and } k = \frac{\lambda}{(-\sigma)k_{str}\,\mathrm{Re}^{-0.25}} \tag{6}$$

where $\sigma = \frac{\tau_0}{\tau}$ - specific shear stress; k_{str} - 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 Gusev (2009), Berta et al (2016):

$$c_p = 30\,\%;\ \sigma = \frac{\tau_0}{\tau_0 + \eta_{ef}\dot{\gamma}};\ \tau_0 = 0.124 \cdot 10^{4{,}525 \cdot c_s} = 0{,}124 \cdot 10^{4{,}525 \cdot 0{,}3} = 2{,}82\ \text{Pa};$$

$$\eta_{ef} = 6.31 \cdot 10^{1{,}72 \cdot c_p} = 20.7 \cdot 10^{-3}\ \text{Pas};\ \dot{\gamma} = \frac{8v}{D_p} = \frac{8 \cdot 1.41}{0.05} = 225.6\ \text{s}^{-1};$$

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

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

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

We use the Blasius formula

$$\lambda = \frac{0{,}3164}{\mathrm{Re}^{0.25}} = 0.04\,.\ k = \frac{0.04}{2 \cdot (1-0.376) \cdot 1.4 \cdot 4305^{-0.25}} = 0.1855$$

The head loss according to formula

$$i = 0.1855 \cdot 4305^{-0{,}25}\ \frac{1.41^2}{2 \cdot 9.81 \cdot 0.05} = 0.05\ \text{mH}_2\text{O/m}.$$

From Table 1 we find that the actual (measured) head loss is 0.046 mH_2O/m. The error of the calculated and experimental data is ±4.8 %.

3. RESULTS

A pilot plant for hydrotransport tests was mounted by employees of PNS-1 Kachkanarsky MCC, Alexandrov et al, (2017). 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 3 m below the steel pipeline. Each pipeline has a measuring section with a length of L = 15 m.

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. Mass concentration of slurry was calculated

$$c_p = \frac{M_{sol}}{M_{fl}} = \frac{M_{sol}}{M_{sol} + M_w}$$

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 slurry 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 Figure 5.

The results of the experiments show that the specific head 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 velocity 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

$$i = \lambda \frac{v^2}{2gD_p} \cdot \frac{\rho_{fl}}{\rho_w}.$$

Table 3

Values of pressure loss according to experimental data

Concentration, %	Density, kg/m^3	Velocity, m/s		Head loss, mH$_2$O/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	3.84	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	1459	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

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

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

The slurry concentration is c_p = 49%. Let us calculate the coefficient of hydraulic resistance (friction factor) according to the formula obtained for the lined pipeline and was obtained during processing of experimental data:

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

For concentration of 49% the slurry density is 1517 kg/m^3, the slurry velocity is 3.15 m/s. The head loss in lined pipeline with diameter of 200 mm is

$$i = 0.029 \frac{3.15^2}{2 \cdot 9.81 \cdot 0.2} 1.517 = 0.111 \text{ mH}_2\text{O/m}.$$

Relative reduction of head loss in lined pipeline is 79%

$$\varepsilon = \frac{i_{cm}}{i_{\phi ym}} = \frac{0,199}{0,111} = 1,79\,;\ \varepsilon_1 = \frac{i_{cm} - i_{\phi ym}}{i_{\phi ym}} 100\% = \frac{0,199 - 0,111}{0,111} 100\% = 79\%.$$

The conversion of pressure loss values for the lined pipeline was performed when operating at other concentrations (Table 3, Figure 5). Figure 5 shows that over the entire range of concentrations of slurry, the head loss in the lined pipe with polyurethane coating DN190 pipeline is not less than 1.75 times lower than in the steel DN200 pipeline without coating.

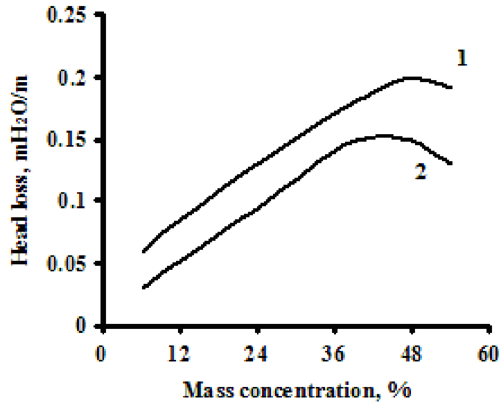

Figure 4. Head loss in pipes during changes of slurry concentration: 1 – steel pipe D_p = 200 mm; 2 – lined pipe D_p = 190 mm

4. CONCLUSIONS

1. 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.
2. 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%.

3. 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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