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ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ТРАНСПОРТНЫХ ТРУБОПРОВОДОВ ЗАКЛАДОЧНОГО КОМПЛЕКСА ПРИМЕНЕНИЕМ ПОЛИУРЕТАНОВОГО ПОКРЫТИЯ

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Аннотация: Одной из основных причин недостаточной эффективности закладочных комплексов горных предприятий является интенсивный гидроабразивный износ его транспортных трубопроводов, который влечет за собой изменение шероховатости внутренней поверхности, что в свою очередь определяет потери напора при гидротранспортировании. Замена изношенных трубопроводов на новые, а также повышенное энергопотребление являются основными статьями расходов при эксплуатации гидротранспортных систем закладочных комплексов. В статье представлены результаты исследований поверхности трубопроводов закладочных комплексов, установлено влияние шероховатости внутренней поверхности трубопровода на удельные потери напора, что позволило произвести оценку экономической эффективности замены толстостенных стальных труб на металлические с футеровкой полиуретаном. Выполнен сравнительный расчет затрат на укладку и эксплуатацию сроком 10 лет стального толстостенного трубопровода и стального трубопровода с внутренним полиуретановым покрытием, учитывающий расходы на закупку, монтаж и замену труб, а также траты на электроэнергию для транспортирования закладочной гидросмеси по этим трубам.

Ключевые слова: закладочный комплекс, гидросмесь, полиуретановое покрытие трубопровода, шероховатость трубопровода, потери напора.

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Increasing the Efficiency of the Transport Pipelines of the Stowing Complex with the Application of a Polyurethane Coating

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Abstract: One of the main reasons for the insufficient efficiency of backfill complexes of mining enterprises is the intense hydroabrasive wear of its transport pipelines, which entails a change in the roughness of the inner surface, which in turn determines the pressure loss during hydrotransportation. The replacement of worn-out pipelines with new ones, as well as the consumption of electricity, are the main items of expenditure in the operation of the hydrotransport systems of stowing complexes. The article presents the results of studies of the surface of pipelines of stowing complexes, the influence of the roughness of the inner surface of the pipeline on the specific pressure loss is established, which made it possible to evaluate the economic efficiency of replacing thick-walled steel pipes with metal pipes with a polyurethane lining. A comparative calculation of the costs of laying and operating a thick-walled steel pipeline and a steel pipeline with an internal polyurethane coating for a period of 10 years was carried out, taking into account the costs of purchasing, installing and replacing pipes, as well as spending on electricity for transporting backfill slurry through these pipes.

Key words: stowing complex, slurry, polyurethane coating of the pipeline, pipeline roughness, pressure loss.

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1. Introduction

The laying of the produced space is used to manage mining pressure, reducing the losses of minerals in the bowels, the excavations of blessed security targets, the prevention of underground fires and sudden emissions of coal and gas, reduce the deformation of the Earth's surface and protection from the destruction of objects in the developed territories, and the abandonment of the rock from the passage work, increasing the safety of mining [1, 2, 15].

The analysis of the work of the branding complexes showed that one of the main reasons for the insufficient efficiency of the branding complexes is the intense hydroabrasive wear of its transport pipelines, which entails a change in the roughness of the inner surface. A change in the roughness of the pipeline affects the loss of pressure. The main factors affecting the intensity of hydroabrasive wear can be divided into two groups [3—7, 13]:

1) factors that determine the value of the kinetic energy of the flow of an abrasive slurry;

2) factors determined by the properties of the wear and wear materials.

2. Materials and methods

To study the elements of hydrotransport systems of stowing complexes, an experimental setup was developed at the St. Petersburg Mining University (Fig. 1). The main elements of the experimental setup are: 1 — centrifugal sand pump P12.5 with asynchronous electric drive (main and backup); 2 — pipeline system; 3 — supply tank; 4 — shut-off valves; control and measuring equipment (5 — pressure switch, 6 — flow meter, 7 — temperature sensor), 8 — flange connection of pipeline parts.

It is envisaged that the samples of the investigated pipes can be in two versions:

1. In the form of a cylindrical insert with a length of 70 mm and an internal diameter of 25 mm, which is installed in a specially provided section of the pipeline (Fig. 2a);

2. As a separate part of the pipeline with a length of 200 mm and an internal diameter of 50 mm, which is mounted in the system with a flange connection (Fig. 2b).

Backfilling slurry based on tailings of iron ore dressing, taken directly from the mining enterprise, is used as the transported abrasive material. The mass concentration of the slurry that the hydrotransport unit is capable of pumping is about 70%. The parameters of the slurry used in the studies are presented in Table 1.

To develop hydroabrasive wear on the inner surfaces of the test samples, the slurry was continuously pumped through a closed pipeline.

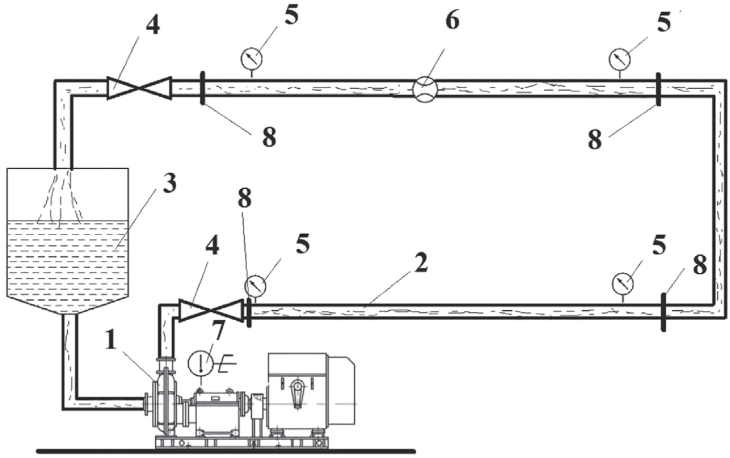

Fig. 1. Scheme of the experimental hydrotransport installation

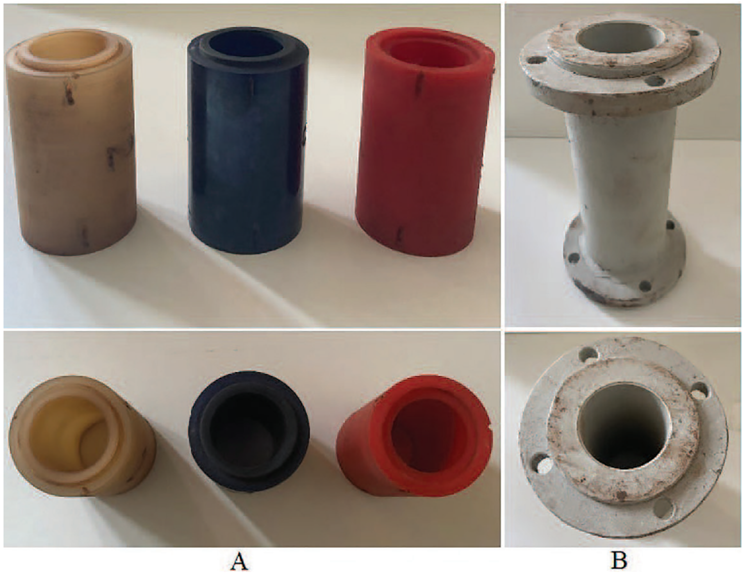

Fig. 2. Test specimens: a — length 7 mm, inner diameter 25 mm; b — length 200mm, inner diameter 50 mm

The mass of the studied samples was recorded before the first test cycle and after each cycle using a high-precision balance AND DL-5000 (Fig. 3a). The value of hydroabrasive wear was estimated from the results of sample mass loss [7, 8]. The Wika PSD-4 electronic pressure switch (Fig. 3b) measures and displays the current pressure in the system. The flow rate and volume of the pumped slurry were monitored using an ultrasonic flow meter Portaflow D550 (Fig. 3c).

Before starting the first test cycle, the mass and roughness of each pipeline sample under study were measured. The roughness of the inner surface of the pipeline affects the pressure loss and, accordingly, the energy consumption.

Table 1
Parameters of the experimental slurry

Weighted average diameter of solid particles, mm	0,49
Density, kg/m^3	1540
Mass concentration, %	50
Volume concentration, %	23
Abrasiveness	heavy

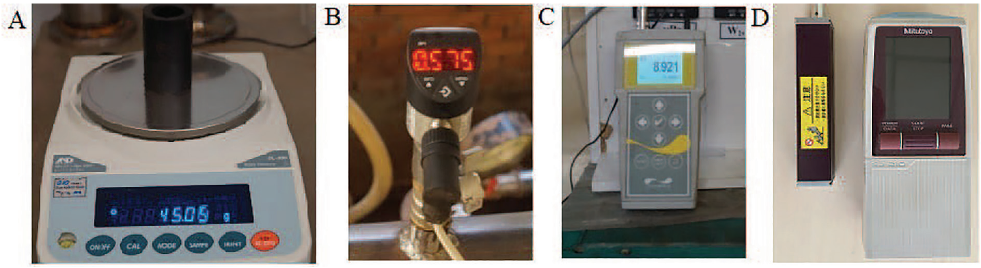

Fig. 3. Control and measuring devices of the experimental hydrotransport installation: a — scales AND DL-5000; *b —* electronic pressure switch Wika PSD-4; *c —* ultrasonic flow meter Portaflow D550; *d —* contact profilometer Surftest SJ-210

The duration of one test cycle was 100 hours, after which the hydrotransport unit was stopped to dismantle the samples. Next, the test elements were thoroughly washed and dried. Drying of metal samples was carried out in a natural way at room temperature for 24 hours. Drying of non-metallic samples was carried out artificially in an oven at a temperature of 70 — 90°C for also 24 hours. The dried tube inserts were reweighed.

To study the nature of hydroabrasive wear of the tested materials, the inner surfaces of the pipes were studied using a Leica DMILM light microscope and their roughness was measured with a Surftest SJ-210 instrument (Fig. 3d).

For testing, pipe sections were made with inserts from the following polyurethanes (Table 2):

The value of the initial roughness is determined by the sample manufacturing technology, which is unique for each manufacturer [10, 28, 49]. For hydrotransport conditions, it is preferable to have the smallest surface roughness of the coating, because the magnitude of the roughness affects the resistance to the movement of the slurry flow during contact friction on the internal surfaces of the pipeline [11, 19, 39–41]. Measurements of the initial surface roughness of coatings of prototypes were carried out along three internal generators along the length of the sample with a rotation of 120° on each of the two sides. The total number of roughness measurements for one element is 6. The obtained values were averaged. The arithmetic mean Ra was taken as the absolute surface roughness Δ. The results of each measurement were displayed on the computer display in the form of a spectrogram (Fig. 4) and the corresponding values of Ra (μm). The obtained measurements of roughness made it possible to preliminarily estimate and compare the values of the roughness coefficients and hydraulic resistance coefficients of pipe samples from different materials, as well as to determine the specific head loss [14, 16, 35].

The coefficient of relative roughness of the inner wall of the pipe is a calculated value that characterizes the coefficient of hydraulic resistance [24, 31–34]:

Table 2
Experimental samples of the pipeline

Sample No.	Material	Shore Hardness
1	Polyurethane E-83	83
2	Polyurethane E-243	90
3	Polyurethane N-802	85

Fig. 4. Spectrogram of the initial roughness of the inner surface of sample 1

$$\varepsilon = \frac{\Delta}{D}, \quad (1)$$

where ε is the coefficient of relative roughness; Δ is the absolute roughness of the inner surface of the pipeline, mm; D is the diameter of the pipeline.

As can be seen from expression (1), the value of the relative roughness coefficient depends on the diameter of the pipeline.

The values of the absolute roughness of the inner surfaces of steel and polyurethane-lined pipes, measured by a profilometer, make it possible to determine the relative roughness coefficients for pipelines of hydraulic transport systems of stowing complexes [17, 52].

The coefficient of hydraulic resistance λ is a complex function of the roughness coefficient and the Reynolds number characterizing the flow regime of a substance [20, 29, 46].

Under laminar and transient regimes of slurry flow, the coefficient of hydraulic resistance does not depend on the roughness of the inner surface of pipelines and is calculated using the Stokes and Blasius formulas, respectively [21, 36–38].

In cases where the slurry flow regime is developed turbulent, the coefficient of hydraulic resistance does not depend on the Reynolds number, but is determined by the relative roughness coefficient ε, in accordance with the Shifrinson formula [25, 47, 51]:

$$\lambda = 0{,}11\varepsilon^{0{,}25}. \quad (2)$$

As a result of calculations using expression (2) of the values of the coefficients of hydraulic resistance for pipelines made from the materials studied in the experiment, it is possible to correlate the specific head losses for pipelines from these materials, because the ratio of hydraulic resistance coefficients is equal to the ratio of specific pressure losses. Analytical dependencies for determining pressure losses and the coefficient of hydraulic resistance can be used to analyze and determine losses along the length for non-Newtonian fluids [23, 42, 53]. Thus, formula (1) will take the form:

$$\lambda = 0{,}11(\frac{\Delta}{D})^{0,25}. \quad (3)$$

3. Experimental studies of pipelines of stowing complexes

Roughness of polyurethane pipelines

The results of determining the arithmetic mean values of the absolute roughness of prototype pipelines according to spectrograms and tabular values are shown in Table 3.

The results of determining the arithmetic mean values of the absolute roughness of steel samples of new and run-in pipelines are shown in Table 4.

Comparison of the roughness of polyurethane-coated pipes (Table 3) and the roughness of steel pipes (Table 4) shows that the roughness of the latter is approximately 4 times higher than the surface roughness of coated pipes. We also note that the Shore hardness of the surfaces of polyurethane coatings does not significantly affect the roughness value.

The values of the absolute roughness of the inner surface of the polyurethane experimental samples and steel pipes measured by a profilometer (Table 3 and Table 4) make it possible to calculate the relative roughness values for the materials of the pipes of the hydraulic transport system of the stowing complex (Table 5). For the calculation, two pipeline diameters were taken — 900 and 1000 mm, as the most commonly used in the hydraulic transport systems of stowing complexes.

The histogram of relative roughness coefficients for steel and polyurethane-lined pipes is shown in Fig. 5.

From the histogram in Fig. 5, it can be seen that the values of the relative roughness coefficients of the inner surface of steel pipes (new and after operation) are 4–4.5 times greater than those of pipes with polyurethane lining.

Table 3

The results of measuring the surface roughness of prototype pipes coated with polyurethane

Measuring point	**example 1, hardness 83A**			**example 2, hardness 90A**			**example 3, hardness 85A**		
	Line I	**Line II**	**Line III**	**Line I**	**Line II**	**Line III**	**Line I**	**Line II**	**Line III**
	Measured roughness values (Rai), μm								
A	1.343	0.379	0.54	0.780	0.798	0.636	1.266	0.642	0.564
B	0.73	0.996	0.696	0.799	0.730	0.726	1.389	1.248	0.877
C	0.893	0.57	0.457	0.91	0.554	0.412	0.876	1.039	1.135
R_a	0.988	0.648	0.564	0.830	0.694	0.591	1.177	0.976	0.859
$\mathbf{R_{a(avg)}} = \Delta$	0.734			0.705			1.004		

Table 4

Measured values of the roughness of the inner surface of steel pipelines

Measuring point	**New pipe**			**Pipe after work**		
	Line I	**Line II**	**Line III**	**Line I**	**Line II**	**Line III**
	Measured roughness values (R_{ai}), μm					
A	2.749	2.809	2.821	5.147	4.199	3.883
B	4.742	4.883	4.913	4.2	3.964	4.088
C	4.903	4.358	4.306	4.618	5.199	5.199
R_a	4.131	4.016	4.306	4.618	4.454	4.39
$\mathbf{R_{a(avg)}} = \Delta$	4.053			4.499		

Table 5
Coefficient of relative roughness of steel pipes and pipes lined with polyurethane

Pipe material	Relative roughness coefficient ($\varepsilon \times 10^6$), pipe diameter, mm	
	900	**1000**
Polyurethane, hardness 83A	0,815	0,734
Polyurethane, hardness 85A	1,11	1,004
Polyurethane, hardness 90A	0,783	0,705
Steel, before operation	4,48	3,97
Steel, post-exploitation	5,01	4,53

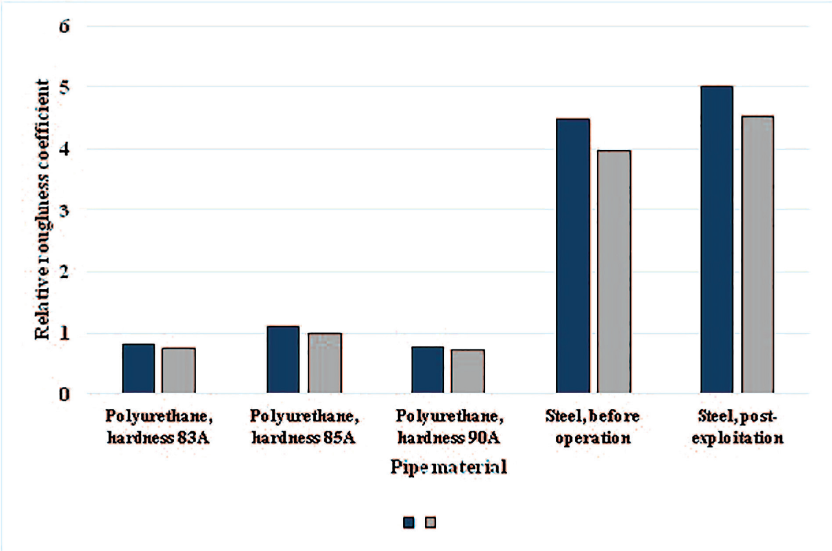

Fig. 5. Coefficient of relative roughness of coated and uncoated pipes

Determination of hydraulic resistance coefficients

According to previous studies, it is known that the slurry flow regime in pipelines is a developed turbulent one [22, 48, 50].

With a developed turbulent regime (quadratic friction zone), the coefficient does not depend on the Reynolds number, but is determined by the relative roughness coefficient, in accordance with the Shifrison formula (2). The values of the coefficient of hydraulic resistance for the pipes under consideration are determined by formula (2) and are indicated in Table 6, and the histogram of these values is shown in Fig. 6.

Based on the data in Table 6, it can be seen that the coefficient of hydraulic resistance for steel pipes is on average 1.5 times higher than for pipes lined with polyurethane.

Pressure loss during hydraulic transport of backfill mixtures

The specific pressure losses of the filling mixture are given in Table 7. Fig. 7 shows a histogram of pressure losses for steel and polyurethane-lined pipelines.

The calculated values (Table 7) show that the specific pressure loss in pipelines with polyurethane lining is 1.5–1.6 times less in comparison with steel pipelines.

4. The discussion of the results

We will evaluate the effectiveness of using metal pipes with a polyurethane

Table 6
Hydraulic resistance coefficient of the inner surface of steel and polyurethane-lined pipes

Pipe material	Hydraulic resistance coefficient (λ)			
	$\varepsilon \times 10^6$	*D* = 900 mm	$\varepsilon \times 10^6$	*D* = 1000 mm
Polyurethane, hardness 83A	0,815	0,0033	0,734	0,0037
Polyurethane, hardness 85A	1,11	0,0036	1,004	0,004
Polyurethane, hardness 90A	0,783	0,0032	0,705	0,0037
Steel, before operation	4,48	0,0049	3,97	0,0057
Steel, post-exploitation	5,01	0,0053	4,53	0,0061

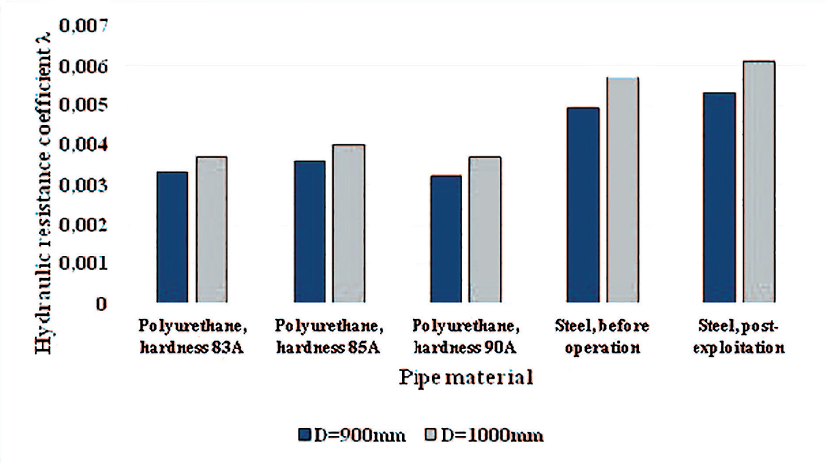

Fig. 6. Hydraulic resistance coefficient of steel and polyurethane-lined pipes

Table 7
Coefficients of specific head loss, hydraulic resistance and relative roughness for a pipeline with a diameter of 1000 mm

Inner surface of the pipe	Absolute roughness, μm	Relative roughness ($\times 10^6$)	Hydraulic resistance coefficient	Specific head loss, m/m
Polyurethane, hardness 83A	0,734	0,734	0,0032	0,012
Polyurethane, hardness 85A	1,004	1,004	0,0035	0,013
Polyurethane, hardness 90A	0,705	0,705	0,0032	0,012
Steel, before operation	4,05	4,05	0,005	0,0198
Steel, post-exploitation	4,49	4,49	0,0051	0,020

inner coating in backfilling complexes based on the indicators of the existing hydrotransport system.

The total costs for the construction and operation of the technological chain of thick-walled steel slurry pipelines for the considered ten-year period of operation are made up of [26, 45]:

1. Capital costs for laying new thick-walled pipes of slurry pipelines, total length 2050 m. Thus, the cost of purchasing and installing 2050 meters of slurry pipelines will be 97.34[1] million rubles.

[1] A total of 2050 m of steel pipe is laid, including slurry line No. 203 — L = 550 m, as well as a section

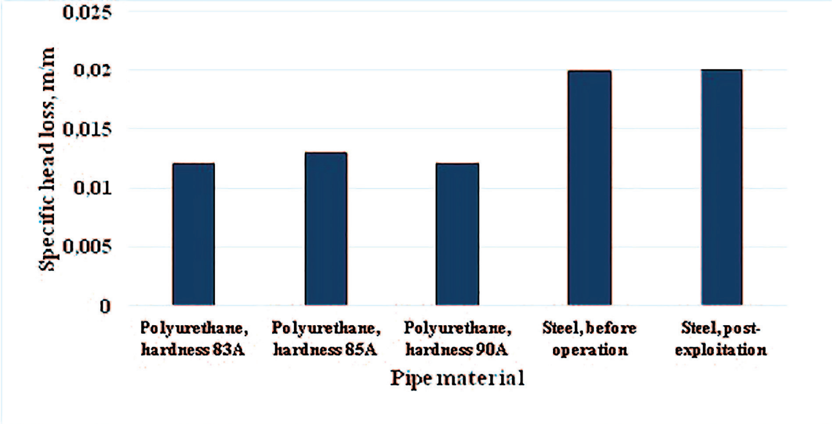

Fig. 7. Specific head loss in steel and polyurethane-lined pipelines

2. Operating costs for the replacement of worn pipes over the period of ten years of operation of the slurry pipeline are 1447.75 million rubles.

3. The cost of electricity for the transportation of slurry over the period of ten years of operation is 882.7 million rubles.

The total costs for the construction and operation of the technological chain of slurry lines for the considered ten-year period of operation amount to 2395.39 million rubles.

In the case of choosing pipelines with a polyurethane internal coating, the costs will be:

1. Capital costs for laying new lined pipes with a total length of 2050 meters will amount to 149.65 million rubles. (the cost of 1 running meter of pipe is 70,000 rubles, the cost of installing 1 running meter of pipe is 3,000 rubles).

2. Operating costs for the considered 10-year period of operation will be 0 rubles. according to the warranty obligations, the company-manufacturer of lined pipes JSC "SOMEKS" provides a 10-year warranty for its products and declares the estimated life of the slurry lines is 25 years.

3. The cost of electricity for pulp hydrotransport over 10 years of operation will amount to 693.8 million rubles.

Comparative indicators of economic costs are shown in the histogram (Fig. 8).

One of the main reasons for doubting the feasibility of replacing steel pipelines with pipelines with polyurethane lining is the cost of their purchase and installation [27, 30, 44]. Capital costs when using polyurethane-coated pipes are 1.5–2 times higher than when using steel pipes. However, the analysis of the use of polyurethane-coated pipelines and comparison with uncoated steel pipes shows that, in addition to energy, an economic effect is also provided, which is achieved already in the first 3 years of operation of the hydrotransport system and in 4 years a full payback of capital costs is provided.

5. Conclusions

The performed analytical and experimental studies have confirmed

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of slurry line No. 303 — L = 1500 m. Weight of 1 line m of pipe 1020 × 22 = 0.541 tons. The total number of pipes is: 2050×0.541=1109.05 tons. The cost of 1 ton of pipe is 85,000 rubles. Total cost of purchasing pipes: 85,000 × 1109.05 = 94.27 million rubles. The cost of installation of 1 meter of pulp line is 1500 rubles. The total cost of installation of 2050 m of pipe: 2050 × 1500 = 3.07 million rubles. The total cost of purchasing and installing a thick-walled pipe will be 94.27 + 3.07 = 97.34 million rubles.

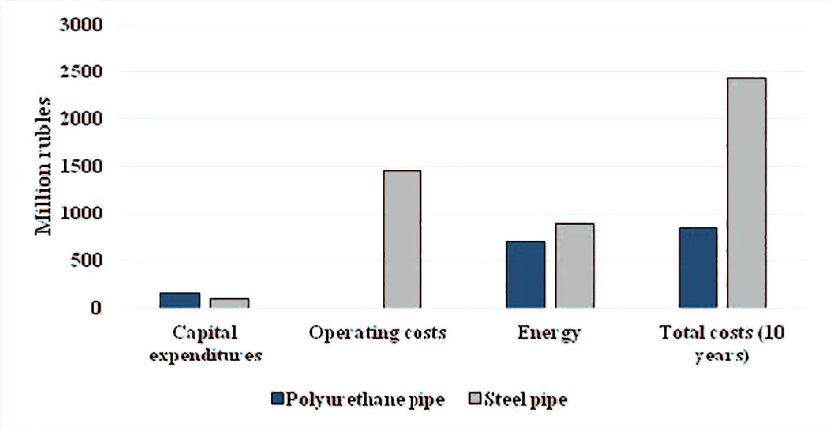

Fig. 8. Costs for laying and 10-year operation of steel pipelines and pipelines with internal polyurethane coating

the significant energy and economic efficiency of the use of polyurethane coatings on the inner working surface of the slurry pipelines of the hydraulic transport system of backfill complexes. As a result of instrumental measurements of the surface roughness of the polyurethane coating, it was established:

1. The physical roughness of the surface of the polyurethane coating in the initial period of operation of the slurry pipeline (new coating) is Δ_{agvmin} = = 0.815 microns. In the process of pipeline operation (T_{work} ≈ 2 years, 16000 hours), and long-term contact of the coating surface with solid abrasive particles of enrichment tailings, the value of physical roughness monotonously increases and reaches a maximum value of Δ_{avg} = 2.4 μm. The maximum achievable surface roughness (steady-state roughness) is Δ_{avgmax} = 2.69 μm.

2. The surface hardness of polyurethane coatings according to Shore in the range of values from 83A to 90A (experimental coatings) has no practical effect on the intensity of changes in the surface roughness of the coating.

3. Hydraulic resistance of slurry pipelines during hydraulic transportation of tailing slurry with a mass concentration of the solid phase c_p = 10% is proportional to the ratio of the equivalent roughness (K_E) to the diameter of the pipeline (according to the formula $\lambda = 0{,}11\left(\frac{K_E}{D}\right)^{0{,}25}$). For the working diameter of the pipeline D = = 1000 mm, when operating in the zone of quadratic friction (developed turbulent regime of the slurry flow), the coefficient of hydraulic resistance on average for the entire estimated life of the pipeline (T_{work} = = 8 years) is λ_{avg} = 0.004).

4. Calculated values of specific head loss during transportation of filling slurry with a mass concentration of the solid phase of 10% through a pipeline with an internal polyurethane coating are 1.5 times less than in a steel pipeline.

5. The total cost for 10 years of operation of standard steel pipelines is approximately 2.5 billion rubles compared to 1 billion rubles in the case of using a pipeline with a polyurethane lining. Consequently, the life cycle costs for 10 years of operation of slurry pipelines with polyurethane coating are 2.5 times cheaper than the operation of thick-walled steel pipes of slurry pipelines.

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