Efficiency of Using Polyurethane-lined Pipes in Hydrotransport Systems of Slurry Tailings

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Abstract. The paper considers the influence of solid phase concentration in slurry flow and its viscosity on the process of pipeline transportation. In view of carried out researches it was assumed that slurry viscosity is proportional to solid particles concentration. The dependence of effective viscosity coefficient on slurry concentration is determined. Calculation of specific pressure drops for hydraulic transportation of concentration tailings is made with and without rheological properties of the thickened slurry tailings. The feasibility assessment of using polyurethane-lined steel pipes in the operating hydraulic transport tailings system of the Kachkanarsk Mineral processing plant is given. The comparison of total capital expenditure and operational costs for each of the considered options of the hydraulic transport system development is made. It has been estimated that the cost advantage is about 1060.38 million rubles for the operation period of 10 years of one technological chain of polyurethane coated pipeline with the diameter of 1000 mm in comparison with the traditional steel pipeline without such coating in the conditions of tail facilities of the Kachkanarsk Mineral processing plant.

1. Introduction
Hydraulic transportation of ore tailings is a difficult technological process which efficiency is determined by a set of factors. Their interrelation is caused by physics of process movement of two-phase flow. The theoretical dependences describe this process in general. The determination of their application is one of the main objectives of the pilot studies.

The most significant parameters influencing the pipeline transportation process are solid phase concentration in slurry flow and its viscosity. In view of carried out researches it was assumed that slurry viscosity is proportional to solid particles concentration without defining a function type and formula describing this dependence. Determining experimental dependence of slurry tailings viscosity on solid particles concentration is one of the key tasks of the pilot studies [1-5].

2. Formulation of the problem
According to the experiments for slurries clarification in order to subdivide them into solid and liquid phases, the conclusion has been drawn that slurry tailings of iron ore of the Kachkanarsk Mineral processing plant belong to liquid systems with non-uniform solid particles. The particles with the size of 0.071 mm (about 30%) are able to form a spatial structure with rheological properties performance in the form of shear stress and viscosity. While increasing concentration of solid phase, and respectively, the size particles of 0.071 mm, the rheological properties are more obvious than in small concentration.
The minimal viscosity has been determined with solid mass concentration of 10% - 0.1 Pa·s, and the maximum viscosity at solid weight content of 60% - 0.68 Pa·s. While increasing solid mass concentration to 20%, the initial shear stress comes out that proves formation of a slurry internal structure. With its concentration increase the intensity of initial stress increases.

The experimental curve of viscosity is well approximated by exponential function:

$$\eta_{ef} = (6.31 \cdot 10^{-3}) \cdot 10^{1.72c_p}. \quad (1)$$

The formula (1) is derived from processing experimental results and presenting experimental data $\eta_{ef}(c_p)$ as $\log \eta_{ef}(c_p)$. The calculation results are given in the graph lines (Fig. 1 a, b). The straight line in the graph is expressed by the function:

$$\log \eta_{ef} = 0.8 + 1.72c_p \quad (2)$$

According to the experimental data, the influence curve of initial shear stress from solid phase concentration (Fig. 1 c) has been plotted:

$$\tau_0 = 0.124 \cdot 10^{4.52c_p} \quad (3)$$

![Figure 1](image)

**Figure 1.** a - Dependence of slurry effective viscosity on mass concentration of solid particles in slurry flow; b - curve approximation $\eta_{ef} = f(c_p)$; c - dependence of initial shear stress on solid particles concentration

The main rheological properties of iron ore slurry tailings of the Kachkanarsk Mineral processing plant are deduced from the experiments in the changing range of mass concentration in slurries from 10 to 60%. The approximations of experimental influence curves of viscosity and extreme shear stress from solid particles concentration of slurry tailings are received.
Specific pressure drops calculations for hydraulic transportation of slurry tailings are made based on the experimental results of the two techniques - with and without rheological properties.

According to the calculation procedure considering rheological properties of the thickened slurry tailings, it is viscoplastic liquid with the initial yield stress $\tau_0$ which function is slurry concentration [6-10].

The mathematical model of visco-plastic liquids is described by Shvedov and Bingam equation

$$\tau = \tau_0 + \eta_0 \dot{\gamma}.$$  \hspace{1cm} (1)

The parameters $\tau_0$ and $\eta_0$ are determined experimentally. The shear rate for the laminar region of slurry flow is a function of the average slurry shear rate and the pipeline diameter, i.e.

$$\dot{\gamma} = f(v_{av}, D) \quad [11-14].$$

We will consider influence of large particles, which diameter is more than $d = 0.071$ mm, and presence of the turbulent mode flow to be a coefficient of the structure $k_{str} = 1 + 3.45 c_{ob}$.

In the case of calculating hydrotransport parameters without rheological properties, the thickened slurry is considered to be heterogeneous liquid including a liquid phase and a non-uniform particle size solid phase [15-17]. At the same time, energy for slurry transportation is spent on transportation of the liquid phase (equation Darci-Veysbakh) and transportation of the solid phase in the critical velocity mode calculated by the empirical formula:

$$v_{cr} = 8.3 \cdot \frac{\sqrt{D}}{\pi} \cdot \sqrt{c_{ob} \rho_{av}}$$  \hspace{1cm} (4)

The average velocity of slurry flow in pipelines is calculated with the assumption that it is equal to critical velocity [18, 19]. Such method of determining slurry velocity flow allows one to avoid uncertainty of pipeline diameter calculation.

3. The results of research

The calculations are made for steel pipeline without internal coating and steel pipeline with a polyurethane coating of the internal surface. The basic data of slurry tailings transportation are accepted according to the design data of the Kachkanarsk Mineral processing plant:

- tailings output is $A_{sol} = 42.6$ million tons/year (4903 t/h, 1486 m$^3$/h = 0.412 m$^3$/s = 1359 kg/s);
- average density of solid tailings is $\rho_{sol} = 3.3$ t/m$^3$;
- estimated flow of the slurry thickened to 40% is $10000$ m$^3$/h = 2.78 m$^3$/s.

The graphic dependences of pressure drop change for tailings slurries transportation calculated by two methods are given in Fig. 2 a and b.

The efficiency assessment of using polyurethane-lined steel pipes for the operating system of tailings hydrotransport of the Kachkanarsk Mineral processing plant is carried out with considering two organization options of the existing technological chain of hydrotransport:

- providing new pipe laying of steel pipe with wall thickness of 22 mm;
- full replacement of the existing steel pipes by new polyurethane-lined steel pipes.

The comparison of total capital expenditure and operational costs for the ten-year operation period has allowed one to determine the most effective and economically feasible option taking into consideration each development option.
According to the calculation, the minimum allowable wall thickness of the main pipeline is 10 mm considering technological chain of hydrotransportation which provides necessary durability. Thus, the pipe stock of hydroabrasive wear for tailings hydrotransportation is defined as 12 mm difference between initial wall thickness of the pipeline and minimum allowable wall thickness of the pipeline.

4. The discussion of the results

According to the measurements of the operational service of the Kachkanarsk Mineral processing plant, intensity of steel pipe hydroabrasive wear for tailings hydrotransportation is 1.5 mm per 1000 h of pipeline operation.

Thus, the operating time of the main pipeline before replacement is 8000 h. The average operating time of the main pipeline is about 3984 h/year. The necessary number of main pipe line replacements is defined as the relation of the general operating time of pipeline for 10 years of operation by the time of main pipeline replacement. For the ten-year period of the main pipe line operation it is to be replaced five times in the case of laying steel pipe with wall thickness of 22 mm. Taking into account calculated frequency of pipeline replacement for 10 years of operation, it will be necessary to lay 1487.8 t (2750 m) of steel pipe.

The efficiency of using internal polyurethane coating of steel pipelines is determined by a considerable decrease of specific pressure drops that has been earlier determined according to the developed calculated methods [20-22] (Table 1).

| Pipeline                              | Parameters                        |          |          |          |          |
|--------------------------------------|-----------------------------------|----------|----------|----------|----------|
|                                      | material roughness $\Delta$,      | equivalent roughness $K_e$, | hydraulic resistance coefficient, $\lambda$ | specific pressure drops $I$, mm wg/m |
|                                      | micron                            | micron   |          |          |          |
| With polyurethane coating            | 0.913                             | 1.772    | 0.004    | 0.0155   |
| Steel without polyurethane coating   | 4.49                              | 14.1     | 0.007    | 0.0232   |

Table 1. Calculated values of roughness coefficient, hydraulic resistance coefficient and specific pressure drops (pipeline D = 1000 mm, operating time $T_{oper} = 1000$ h)
Thus, the required pressure created by pumps of the hydrotransportation technological chain consisting of polyurethane-lined pipes in summer is 172.8 m of the water column whereas in winter, it is 134 m of the water column.

We consider the efficiency of using polyurethane coating as the relation of required pressure in pipelines without polyurethane coating to the pressure in pipelines with polyurethane coating:

\[
\frac{H_{\text{sum}}}{H_{\text{coa}}} = \frac{228.8}{172.8} = 1.32
\]

\[
\frac{H_{\text{wint}}}{H_{\text{coa}}} = \frac{168.8}{134} = 1.26
\]

i.e. in summer time, the required pressure decreases by 32%, in winter time – by 26%.

5. Summary

1. The performed studies have proved considerable power and economic efficiency of using the polyurethane coating for the working surface of steel pipeline in the system of iron ore tailings hydrotransport of the Kachkanarsk Mineral processing plant.

2. Decreasing power costs of hydraulic transport of slurries tailings is provided with considerably less roughness of internal polyurethane coating (1.772 microns) in comparison with roughness of steel pipelines without such coating (14.1 microns).

3. The perspective direction of improving hydrotransport is technological transition to transportation of thickened slurries in the range of weight content of the solid phase from 30 to 60%. In the case of using pipelines with polyurethane coating, the value of specific pressure drops is 14.4 m/km (av = 30%) and 63.6 m/km (av = 60%). The specific pressure drops in steel pipes without coating are 25.2 m/km (av = 30%) and 107 m/km (av= 60%).

4. For the operation period of 10 years of one technological chain of polyurethane-lined pipes with the diameter of 1000 mm in comparison with the steel pipeline without coating in the conditions of tail facilities of the Kachkanarsk Mineral processing plant, the cost advantage is about 1060.38 million rubles.

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