2. Design and justification of operating and structural parameters, as well as economic efficiency of sandwich belt high angle conveyors should take into account that:

- the belt of HAC is much wider than the conventional conveyors have in the same operating conditions but the associate increase in cost can be levelled by the decrease in the conveyor length, which furthermore leads to the decrease in the weight of the metalware;
- the design of the sandwich belt high angle conveyor includes the hugging and the conveying belts which have lower total strength than the conventional conveyor has in the same operating conditions;
- the hugging force of the sandwich belt high angle conveyor is a function of both the belt angle and length, and increases with an increase in the latter.

3. The Russian and foreign research shows that the heavy-duty sandwich belt high angle conveyors provide overwhelmingly higher efficiency than the conventional belt conveyors, especially in operation with the cyclical-and-continuous technology in deep open pit mines.

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ROLLING RESISTANCE COEFFICIENT OF BELT CONVEYOR ROLLERS AS FUNCTION OF OPERATING CONDITIONS IN MINES

The article describes the theoretical and experimental studies into the rolling resistance coefficient of rollers of belt conveyors in mines. The experimental testing based on the theory of similarity and dimensions has produced the relationships of the rolling resistance coefficient, the main structural parameters of bearings and the service properties of plastic lubricants at dynamically varied temperature and different belt speeds and roller loads. The reduction in the rolling resistance force applied to the rollers at the adjusted rolling resistance coefficient makes it possible to increase the operating energy efficiency of belt conveyors in mines due to the rational use of modern plastic lubricants.

Keywords: *belt conveyor, belt resistance calculation, belt conveyor roller, bearing assembly, types of plastic lubricants, operating temperature, roller load, belt speed*

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Introduction

Advancement of mining industry in Russia raises quality standards of mining machinery. No mine is imaginable without transportation, and a specific place in this regard belongs to the conveyor transport [1].

Operating efficiency of a belt conveyor depends on many factors. The conveyor roller is the main component of the conveyor design. The failure-free performance of the conveyor rollers governs the belt service life and the operating reliability of the whole conveyor. Routine failures of conveyor rollers result from the discapability of bearings and bearing assemblies. Bearings fail ahead of the warranty life because of wear of bearing races, corrosion, and faulty and impure lubrication.

Numerous research in the field of improving reliability of conveyor rollers aim at engineering development of bearing seals to protect them from abrasive materials, moisture and impure lubricants. Nonetheless, the life of conveyor rollers is yet shorter than it is specified [2–4]. At the same time, no studies focus on operating reliability of rollers as function of service properties of plastic lubricants used in bearing assemblies when operated in different climatic conditions [5]. The effective viscosity of plastic lubricants is one of the key physical properties which condition the rolling resistance coefficient (RRC) of conveyor rollers. With decreasing temperature, the effective viscosity of plastic lubricants grows, which increases RRC, and this can induce an arrest or wear of a roller when operated under low temperatures [6–8]. The most heavy-duty mines in Russia operate in the North, where negative air temperatures prevail for the most part of the year, which promotes relevancy of the research into the impact of service conditions on the rolling resistance coefficient of conveyor rollers. Adjustment of RRC in the belt pull design on the basis of the obtained results can contribute to the enhancement of reliability and efficiency of belt conveyors.

The analytical review of the studies aimed to find RRC of rollers for mine conveyors shows that the researchers use experimental dependences assisted by currently obsolete technologies and materials [9]. Such dependences describe spending of life of roller bearing assemblies and solve a narrow range of problems earlier addressed by many researchers. In the recent decades, technologies and materials used in manufacture of conveyor rollers advanced greatly. A few generations of plastic lubricants have changed. Roller shells are commonly manufactured from the present-day polymeric materials. Higher accuracy of manufacturing and reduction in cost allows wider application of closed-type bearings. In this connection, in pull design theory, RRC analysis should take into account scientific advances in elasticity theory and in plastic lubricant flow dynamics theory, as wells the impact of rheological phenomena and vibrations in assembles and gears.

The Fuel and Lubrication Laboratory at NUST MISIS undertook experimental investigation using the theories of similarity and dimensions, and obtained the relations of RRC of conveyor rollers with the main design variables of bearings and service properties of plastic lubricants at variable temperatures, rotation speeds and radial forces applied to the rollers.

Research results

The rolling resistance of conveyor rollers was studied using a dedicated mathematical model including the governing factors as follows: design variables of bearings (outside and inside diameters of bearings, diameter of balls); operating temperature (ambient temperature and bearing assembly temperature); type of a plastic lubricant (colloidal compound, effective viscosity, penetration number, recommended operating temperature range); load applied to a roller (cargo weight, belt weight and weight of rolling parts of a roller); rotation speed of a roller. The parameters capable to provide the numerical characteristics of these factors are compiled in the **Table**.

Governing parameters of bearing roller resistance

Parameter	Formula
Outside bearing diameter D, m	L
Effective viscosity μ_{ef},	$ML^{-1}t^{-1}$
Radial bearing load F_r, kg·m/s^2	MLt^{-2}
Roller rotation frequency f, 1/s	t^{-1}
Ambient temperature t, °C	T
Gravitational acceleration g, m/s^2	Lt^{-2}

Using the selected parameters and in accordance with the theories of similarity and dimensions, the basis parameters to be invariable in the experimentation are chosen, and the dimensionless systems are constructed for two variable parameters (radial load and rotation speed:

$\pi_1 = F_r D^{\alpha} \mu_{ef}^{\beta} g^{\gamma}$,

$\pi_2 = f D^{\alpha} \mu_{ef}^{\beta} g^{\gamma}$.

The dimensionless systems constructed using the method of zero dimensions are given by:

$\pi_1 = F_r D^{-3/2} \mu_{ef}^{-1} g^{-1/2}$,

$\pi_2 = f D^{1/2} g^{-1/2}$.

These systems contain no temperature which should be taken into account separately. The relation between the output parameter—RRC (denoted by w_{roll}) and the input parameters represents a power polynomial multiplied by a temperature correction is:

$w_{roll} = f(\pi_1, \pi_2)k(t) = (A_0 + A_1\pi_1 + A_2\pi_2 + \ldots)k(t)$,

where $k(t)$ is the temperature correction in a range from 0 to 1; $k(t) = 1 - \alpha(t - t_0)$; α, A_0, A_1, A_2 ... are the empirical coefficients found experimentally; t_0 is the lowest temperature of applicability of a lubricant.

The benefit of using the similarity theory relations consists in the inclusion of variable parameters in the dimensionless system, which enables application of the experimental dependences for calculating similar objects having different basis parameters [10, 11].

The experimental research of RRC followed a complete three-level factor plan. The ranges of the variable parameters in the experimental research are given below:

f, c^{-1} (min^{-1})	2.5–7.5 (150–450)
F_r, N	130–250
t, °C	−40 ...+30

The regression equation of the empirical dependence represents a complete square polynomial:

$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_{11} x_1^2 + \alpha_{22} x_2^2 + \alpha_{12} x_1 x_2$,

where x_1, x_2 are the coded values of levels of the above-presented two dimensionless systems, assuming the values of −1, 0 and +1.

After the adequacy check and finding statistical significance of individual coefficient, some members may be withdrawn from the regression equation.

The analysis of the existing testing benches and RRC procedures reveals their inappropriateness in solving the problems outlined here. The experimental research is to include the dependence of RRC on the simultaneous change in a number of parameters, for instance, in the temperature and rotation speed of bearings.

The new-developed method and a bench tester fulfill the above requirements in experimental measurement of RRC (**Fig. 1**).

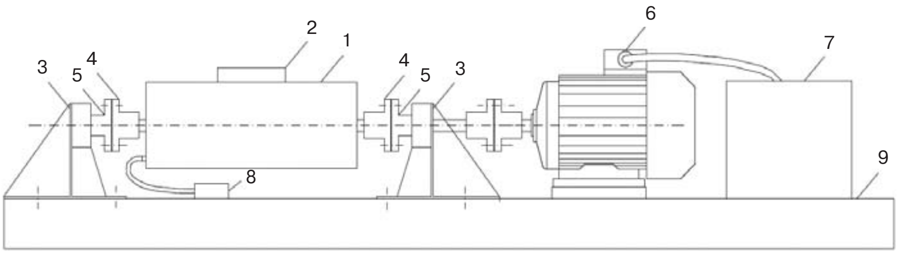

Fig. 1. New bench tester: 1—conveyor roller; 2—load simulator; 3—support; 4—couplings; 5—connecting branches; 6–electric motor; 7—frequency converter; 8—thermocouple; 9—foundation slab

During the tests, the electric motor and roller supports are installed in the guideway, which enables moving and arresting all components of the bench tester. The conveyor roller is connected with the supports via couplings. This preserves the ability of the roller shaft to rotate freely relative to the shell, and ensures rapid and easy installation of the roller. The readily removable roller caps enable easy replacement of bearings, their washing and lubrication. The load imposed on the roller shell was simulated using spherical dead weights with a radial cutout from four-ball machine FBM-1. The real-time measurement of the antitorque moment on the motor shaft and the estimate of change in the roller shaft rotation frequency used Siemens Micromaster-440 frequency converter, courtesy of Intechcom Innovation Center which also provided experts to assist and supervise the experimentation.

On the bench tester, a conveyor roller with diameter of 127 was installed with the radial spherical ball bearings (standard size 6304). For the temperature determination, at the end covers of the roller, a pre-calibrated thermocouple was mounted and connected to an electronic thermometer [12, 13]. In this manner, it is possible to continuously measure the current temperature of a lubricant in the roller bearings.

The roller was cooled down to a testing temperature using a lab-scale fridge with a capacity of –53 °C. The testing procedure sets the initial lubricant temperature in the roller bearings not higher than –40 °C. As the temperature of the roller grows quickly from the moment when it is taken from the fridge and to the moment of mounting on the bench tester, as well as with a view to reduce the rate of the roller heating during operation, the present-day heat-insulation was used. That allowed simulating gradual increase in the temperature of a roller operating under negative temperatures after actuation of a conveyor.

The comparison of variation in the temperature and the antitorque moment on the motor shaft as function of the varied experimental loads and rotation frequencies of the roller provides the empirical dependence of the temperature factor for different lubricants and different operating conditions.

The tests of the roller bearing assemblies used the Russian manufacture lubricants, namely, lithium grease Litol-24 and calcium grease TSIATIM-221, as well as the foreign manufacture lithium grease—Chevron Delo Greases EP—for the comparison.

Every bearing before installation was washed, dried and filled with a lubricant to 60% of its total volume. The trial run of an assembled roller was performed at the rotation frequency of 500 min^{-1} and load at 250 N for an hour [14, 15]. Then, the roller was wrapped in a heat-insulator sheet and placed in the fridge to get cooled down to the temperature of –50 °C. Heat insulation and cooling enables avoiding quick heating of the roller during its mounting on the bench tester and allows starting the tests at the preset temperature of –40 °C.

For greases Litol-24, TSIATIM-221 and Chevron Delo Greases EP, the tests allowed correlating the rolling resistance coefficient w_{roll} of the roller, its loading (130, 190 and 250 N) and rotation speed (150, 300, 450 min^{-1}).

Based on the testing data, the empirical dependences of RRC on the roller loading and rotation speed were constructed.

The dependences of RRC on the varied parameters are given by:

—for Litol-24

$$\begin{aligned} w_{\text{roll}} = \Bigg[& 0.0074 + 0.00055\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2}}{2.46}\right) + 0.00091\left(\frac{fD^{1/2}g^{-1/2}}{0.18}\right) - \\ & -0.0003\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2}}{2.46}\right)^2 - 0.0003\left(\frac{fD^{1/2}g^{-1/2}}{0.18}\right) + \\ & +0.00023\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2} - 7.79}{2.46}\right)\left(\frac{fD^{1/2}g^{-1/2} - 0.36}{0.18}\right)\Bigg][1 - 0.016(t+20)]\,; \end{aligned}$$

—for TSIATIM-221

$$\begin{aligned} w_{\text{roll}} = \Bigg[& -0.0012 + 0.0051\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2}}{2}\right) + 0.0024\left(\frac{fD^{1/2}g^{-1/2}}{0.18}\right) - \\ & -0.0009\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2}}{2}\right)^2 - 0.0009\left(\frac{fD^{1/2}g^{-1/2}}{0.18}\right) + \\ & +0.00023\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2} - 6.33}{2}\right)\left(\frac{fD^{1/2}g^{-1/2} - 0.36}{0.18}\right)\Bigg][1 - 0.0215(t+20)]\,; \end{aligned}$$

—for Chevron Delo Greases EP

$$\begin{aligned} w_{\text{roll}} = \Bigg[& 0.0268 - 0.0103\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2}}{0.99}\right) - 0.0050\left(\frac{fD^{1/2}g^{-1/2}}{0.18}\right) + \\ & +0.0011\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2}}{0.99}\right)^2 - 0.0012\left(\frac{fD^{1/2}g^{-1/2}}{0.18}\right) + \\ & +0.0005\left(\frac{F_r D^{-3/2}\mu_{ef}^{-1} g^{-1/2}}{0.99}\right)\left(\frac{fD^{1/2}g^{-1/2}}{0.18}\right)\Bigg][1 - 0.019(t+20)]\,. \end{aligned}$$

Figure 2 shows the regressions of RRC versus the rotation frequency the roller under maximum loading (see Fig. 2a) and versus the roller load at the maximum rotation frequency (see Fig. 2b) with the test lubricants.

The tests reveal that on a certain interval of negative temperatures, the roller bearing assemblies experience

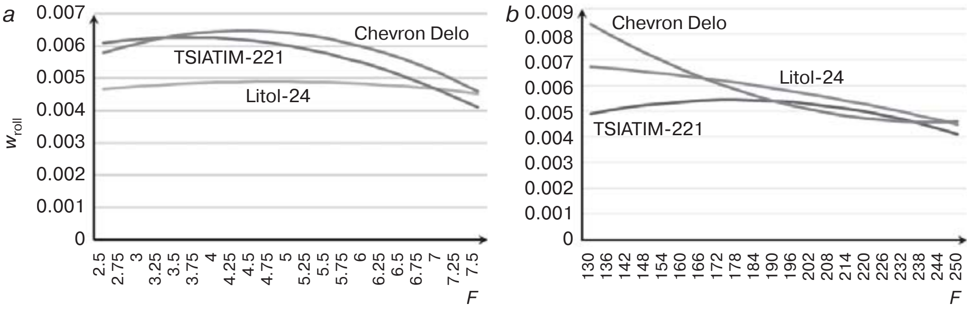

Fig. 2 Regressions of rolling resistance coefficient w_{roll} versus rotation frequency under maximum loading (*a*) and versus load at maximum rotation frequency (*b*) for test lubricants

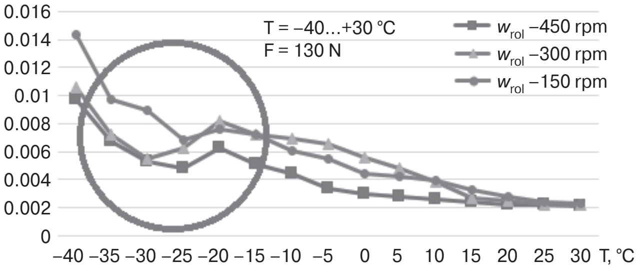

Fig. 3. Temperature interval of rheological phenomena and vibrations

high-frequency vibrations [16–18] accompanied with a drop in the motor shaft resistance and its increase afterwards. This phenomenon appears in the temperature range from −35 °C to −20 °C in the tests of Litol-24 and TSIATIM-221. The minimum value of the antitorque moment agrees with the conditional medium of this temperature range. Above the temperature of −20 °C, the antitorque moment lowers uniformly (**Fig. 3**).

The high-frequency vibrations of the roller bearing assembly in the specified temperature range were accompanied with a high-frequency sound, the level of which dropped as the temperature increased. For the analysis of the vibration and its frequency versus temperatures, three temperature ranges were chosen and three spectra were obtained **(Fig. 4**).

With grease Chevron Delo Greases EP, the high-frequency vibration phenomenon is less pronounced. The rolling resistance changes but not so intensively as in the two previous cases.

For the comparison of the rolling resistance coefficients from the regression equations for different lubricants and the assumed coefficient in calculation of the rolling resistance force of conveyor rollers using the existing procedures, we calculated RRC using the Shahmeyster–Dmitriev approach [19] and compared it with the empirical RRC values obtained for Litol-24. The curves of RRC from two procedures and the linear rotation speed of the roller conveyor shell are presented in **Fig. 5**.

The comparison of the results shows that the use of the new procedure of RRC calculation enables decreasing RRC value by 1.9–2.7 times as against the existing guidance [20].

Conclusions

The accomplished theoretical analysis and experimental investigation of the rolling resistance coefficient of conveyor rollers as function of the main design variables of bearings and the service properties of plastic lubricants at dynamically varied temperature and at different belt speed and roller loading allows producing some conclusions and recommendations as follows:

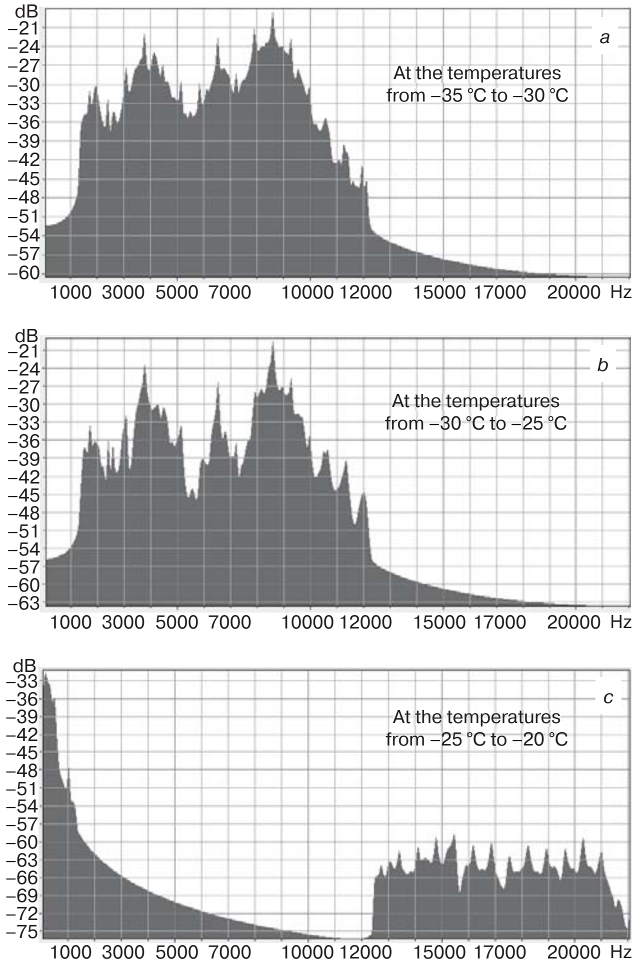

Fig. 4. Vibration spectrum at the temperatures of −35...−30 °C *a*, −30...−25 °C *b* and −25...−20 °C *c*

1. The rolling resistance coefficient (RRC) of conveyor rollers depends essentially on the design variables of bearings, on the ambient temperature, on the type of a plastic lubricant in use, as well as on the radial loads and rotation speeds of the bearings. These factors are sufficiently characterized by such numerical parameters as the outside diameter of a bearing, its total radial loading (including the weight of a roller) and rotation frequency, the effective viscosity of a plastic lubricant and the operating temperature.

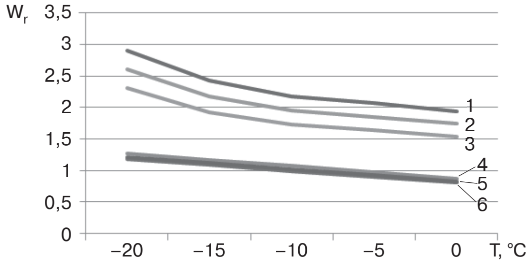

Fig. 5. RRC versus linear speed of rotation W_r of conveyor roller shell:
by existing procedure: 1—at 3 m/s; 2—at 2 m/s, 3—at 1 m/s; *by new procedure*: 4—at 3 m/s, 5—at 2 m/s; 6—at 1 m/s

2. The comparative analysis of the testing data and the theoretical and practical guides on belt conveyor design in the mining industry and on RRC determination shows that RRC in the belt pull design should be decreased by 1.9–2.7 times subject to operating conditions.

3. The operating temperature impact on RRC should be considered separately as the number of dimensions of the basis parameters lacks the dimension of temperature. This impact is taken into account by means of introduction of a thermal factor.

4. The experimental determination of RRC should include concurrent and real-time measurement of the antitorque moment and current temperature of the bearing and the roller rotation speed. This concept is implemented in the new method and bench tester developed for the rolling resistance coefficient determination.

5. Under negative temperatures, at the bottom of their ranges recommended by manufacturers of plastic lubricants, in the contact zones of balls and raceways, the rheological phenomena and vibrations appear, which causes first drop and then jump of the rolling resistance coefficient. For this reason, the lubricants tested at the temperature below –20 °C in this research are unrecommendable for the application.

6. The experimental research of the tested plastic lubricants has shown that the drop of the thermal factor in the temperature range from –20 °C to +20 °C can be assumed as approximately linear, and at the temperatures above 20 °C the thermal factor can be assumed as a constant value. The relationships of RRC, rotation frequency and radial load are sufficiently accurately described by the square parabolas.

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