https://doi.org/10.32056/KOMAG2026.4

Laboratory tribological tests of roller-conveyor belt interaction

Received: 19.03.2026

Accepted: 23.04.2026

Published online: 24.04.2026

Piotr HAŁUBEK [1*], **Piotr KULINOWSKI** [1]

Author's affiliations and addresses:

[1] AGH University of Krakow,
Department of Machinery Engineering and Transport
al. Mickiewicza 30
30-059 Kraków
Poland

*** Correspondence:**

e-mail: halubek@agh.edu.pl

Abstract:

Belt conveyors are widely used for the transportation of bulk materials in mining and heavy industry. One of the major operational challenges in such systems is belt slippage, which may result in structural damage, production interruptions, and increased maintenance costs. In industrial practice, belt tracking is often corrected by skewing idlers; however, excessive skew angles may lead to increased wear of the conveyor belt cover and roller surfaces. Reliable investigation of the tribological phenomena occurring in the roller – conveyor belt friction pair therefore requires experimental testing under controlled laboratory conditions that reproduce real operating parameters.

This study presents the design and application of a dedicated laboratory test rig developed to investigate the tribological interaction between a steel roller and a rubber conveyor belt cover in a roller–roller configuration. The design of the test stand was based on dimensional analysis and mechanical similarity theory in order to ensure geometric, kinematic and dynamic similarity to real conveyor operating conditions. An original measurement method based on the number of revolutions of the samples was used to determine the volumetric wear of cylindrical rubber specimens, allowing long-term measurements without interrupting the experiment and ensuring a measurement accuracy of approximately 3%.

Experimental tests were conducted for several skew angles and operating speeds typical for conveyor systems. The wear intensity index and the coefficient of friction were determined as functions of skew angle, speed, and normal load. The results indicate that the wear intensity increases significantly when the skew angle exceeds approximately 3°, while for angles between 1 ° and 3 ° the wear intensity remains relatively low. The experimentally determined friction coefficient increases with the skew angle and decreases with increasing normal load. The developed methodology enables reliable evaluation of tribological parameters of the roller – belt system and supports optimisation of conveyor design parameters and belt durability.

Keywords: belt conveyor, rubber wear, coefficient of friction, roller – belt system

Publisher: **KOMAG Institute of Mining Technology, Poland**

1. Introduction

Belt conveyors are one of the most widely used means of transporting bulk materials. This is due to their simple design, high efficiency, reliability, ease of operation and automation, and their ability to cover long distances while adapting well to the terrain [1, 2].

One of the key issues in the design and operation of belt conveyors is the proper support of the belt on the rollers. The choice of belt support method should take into account the operating conditions and parameters, the type of material being transported, and the load on the conveyor. The most commonly used solution in mining and heavy industry are steel shell rollers (Fig. 1), which support and guide the belt, ensuring that it remains in the correct position and shape [3, 4].

One of the adverse phenomena that may occur during the operation of belt conveyors is belt slippage. It consists in the belt moving transversely to its intended direction of movement, which may lead to contact between the conveyor belt and the conveyor's supporting structure. Belt slippage and the resulting local damage to the route structure, roller or belt edge can lead to downtime and losses resulting from the interruption of production processes and the need to repair or replace components. Therefore, it is necessary to perform maintenance activities aimed at ensuring the centered belt movement. In practice, it often happens that the centering of the belt is achieved by improper, i.e. excessive, skewing of the side rollers, which causes accelerated wear of the belt cover and the roller surfaces.

Fig. 1. Roller belt support system in an underground coal mine

Abrasive wear is the most common cause of conveyor belt degradation, resulting from direct contact between the rubber cover and the roller shell or an additional abrasive layer – mineral particles, dust, or contaminants. The intensity of wear is significantly influenced by the material properties of the friction pair and mechanical factors such as normal load, slip distance, relative speed, and friction coefficient.

The complexity of wear mechanisms [5, 6, 7] and the difficulty of fully identifying the friction conditions between the rubber cover and the roller limit the possibilities of predictive modelling of belt life and the design of optimal structural solutions [4, 8, 9]. Studying this phenomenon in the context of the correct selection of rubber components used for conveyor belt covers, including flame-retardant and abrasion-resistant belts, requires testing the abrasion resistance of rubber under conditions corresponding to real-life conditions. Conducting such tests in industrial conditions is very difficult due to harsh working conditions, dust, humidity, and the inability to conduct tests under controlled load conditions (Fig. 1). Therefore, the wear characteristics of friction pairs are determined by laboratory experimental tests, during which the wear mechanism and the type and parameters of contact between the elements are reproduced.

A review of the literature indicates that, due to the lack of a unified approach to testing the wear of rubber, researchers focus on designing unique, specialized test rigs that allow for the control of multiple parameters simultaneously and enable testing under conditions similar to those encountered in service, for a specific, individual case. The devices most commonly used to test rubber wear of rubber in conditions involving sliding are test benches based on tribological systems, mostly ‘pin-on-disc’ systems [10, 11, 12, 13] and ‘roller-roller’ systems [14, 15, 16, 17, 18].

The ‘pin-on-disc’ system is used for basic research that enables the analysis of friction phenomena under sliding conditions with point or surface contact. It allows the precise determination of the coefficient of friction and the intensity of wear as a function of sliding speed and contact forces. Due to the high concentration of pressure in the contact area, this system accurately reproduces the abrasive and adhesive processes. It is particularly useful for the initial classification of materials, comparative tests, and analyses of the basic mechanisms of friction and wear.

The ‘roller-roller’ system replicates the complex conditions of linear and surface contact that occur, among others, in the operation of rollers or tires. Its significant advantage is the ability to simultaneously take into account sliding and rolling motion, which enables the analysis of phenomena characteristic of actual operating systems. This configuration allows for reliable testing of abrasion and fatigue wear mechanisms, as well as the formation of contact rollers and viscoelastic deformations typical for elastomers.

A review of the literature indicates that a reliable assessment of the wear intensity of rubber requires experimental testing under conditions as close to actual operating conditions. This allows the proper representation of the complex interaction between the material properties of the rubber, the geometry and kinematics of contact, and load parameters.

However, in industrial practice, there is a lack of experimental test rigs capable of analyzing wear in rubber–steel friction pairs under rolling contact conditions with a skewed rolling element, as occurs in idler–conveyor belt systems. Existing research solutions are primarily focused on rubber wear under sliding contact conditions, tire wear on asphalt surfaces, or the influence of rubber material properties on wear behavior. Consequently, they do not adequately reproduce the combined rolling–sliding contact and kinematic conditions characteristic of skewed idlers in conveyor systems.

The novelty of the present study lies in the development of a laboratory method and a dedicated test rig developed in a ‘roller-roller’ configuration that allow investigation of rubber wear in a roller–belt friction pair under controlled skew conditions, thereby bridging the gap between simplified laboratory tests and real conveyor operation.

2. Materials and Methods

The design and construction of a laboratory stand for model testing of friction pair wear between a roller and a conveyor belt in a ‘roller-roller’ system are presented below. The stand shown in Fig. 2 consists of: a structural frame (4, 5), lever systems with bearings (3), rubber sample mounting systems (1, 2), a steel drum (8) and a drive system with a belt transmission (6, 7). An overview containing key technical parameters of a test stand was presented in Table 1 below.

Publisher: **KOMAG Institute of Mining Technology, Poland**

Table 1. An overview containing key technical parameters of a test stand

Item	Parameter	Data	
		Value	Unit
1	Belt transmission ratio	2:1	-
2	Motor power	1.5	kW
3	Range of counter sample rotation speed	153 – 410	RPM
4	Range of counter sample linear speed	1.6 – 4.3	m/s

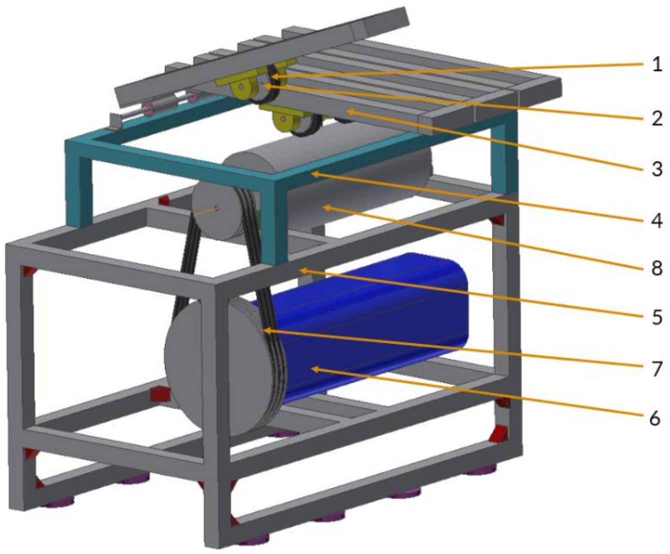

Fig. 2. CAD model of the stand with key elements marked: 1 – Cylindrical rubber sample, 2 – Pressure disc, 3 – Lever system, 4 – Support frame, 5 – Structural frame, 6 – Electric motor, 7 – Belt transmission, 8 – Steel drum (counter-sample)

In the process of designing the test stand, dimensional analysis and mechanical similarity theory [19, 20, 21, 22] were used to ensure the proper representation of the friction between the roller and the conveyor belt. These methods are tools that enable the proper design of the system and the selection of operating parameters, which results in the methodological correctness of the research conducted. The result of applying these methods was the determination of the conditions for the correct representation of the friction interaction between the conveyor belt and the roller: maintaining the applied skew angle (1 to 4 degrees), using friction pair materials as in real conditions (i.e. Young's modulus) and representing the actual load condition. The samples were made of flame-retardant rubber, which is often used in conveyor belt operation. Sample skew angle was defined as the intentional angular misalignment between the axes of the rolling sample and the counter sample, which generates lateral forces and combined rolling–sliding contact conditions.

Key test parameters were presented in Table 2 below.

Table 2. Test parameters

Item	Parameter	Data	
		Value	Unit
1	Normal load	110	N
2	Range of applied skew angle	1 – 4	deg.
3	Sampe rotational speed	810	RPM
4	Sample linear speed	4.3	m/s
5	Number of repetitions	10	-
6	Sample material	Flame-retardant rubber	
7	Sample hardness (Shore)	67	ShA
8	Counter sample roughness	3.2	µm
9	Contact characteristics	Dry (two-body abrasion)	-

The test rig described above uses an original method of measuring wear by indirectly measuring the diameters of rubber components. Diameters are calculated based on the number of revolutions of the samples in proportion to the number of revolutions of the steel drum. The number of revolutions was measured using panel revolution sensors with an inductive sensor (Fig. 3) with a maximum measurement frequency of 30 Hz, mounted on the lever arms and on the structural frame. To record the rotation of the samples (1) and the steel drum, a single magnet (3) was placed on one of the pressure discs (2) of each sample and on the side surface of the drum. For each full rotation of the pressure discs (rubber samples) and rotation of the steel drum (counter samples), a dedicated rotation sensor (4) recorded one pulse. Length of friction path of the sample was defined as the total distance travelled by a sample during rolling motion over the counter sample throughout the test as the product of the number of revolutions of the steel drum and its circumference.

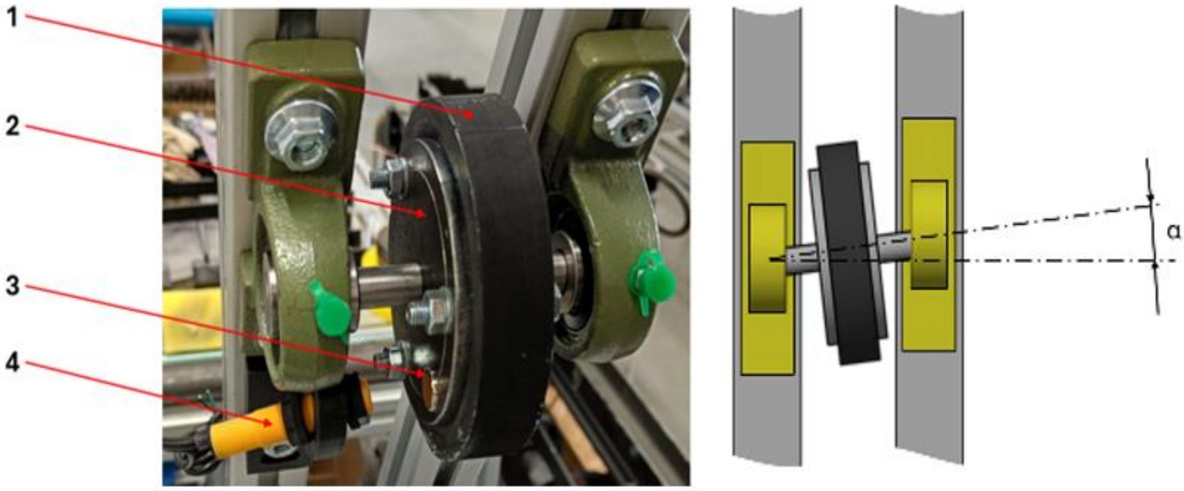

Fig. 3. Sample mounting and rotation measurement system: 1 – Sample, 2 – Pressure disc, 3 – Magnet, 4 – Inductive sensor

As a result of friction between the cylindrical steel drum and the rubber samples, the rolling surface of the less hard element was subject to wear. Due to the material differences between the samples and counter-samples, resulting from the lack of an additional abrasive factor (i.e. copper ore dust), the wear of the cylindrical surface of the steel drum was negligible, which is in line with expectations and the literature [23, 24, 25, 26].

As the rolling surface of the cylindrical rubber sample wore down, its diameter decreased. and the innovative measurement method allowed for a very accurate determination of the volume wear of the samples compared to measuring wear using a laboratory scale. Furthermore, it enabled the wear to be measured without the need to interrupt measurements and dismantle the sample mounting systems. For multiple measurements for a given set of samples, lasting up to several weeks, this significantly reduced the influence of external factors and minimized measurement errors.

3. Results

Below are sample results of tests on the rubber wear intensity index and the friction coefficient for a rubber-steel friction pair operating under rolling slip conditions.

3.1. Wear intensity index

The graphs shown in Figs. 4 and 5 present the test results for a linear drum speed of 4.3 m/s.

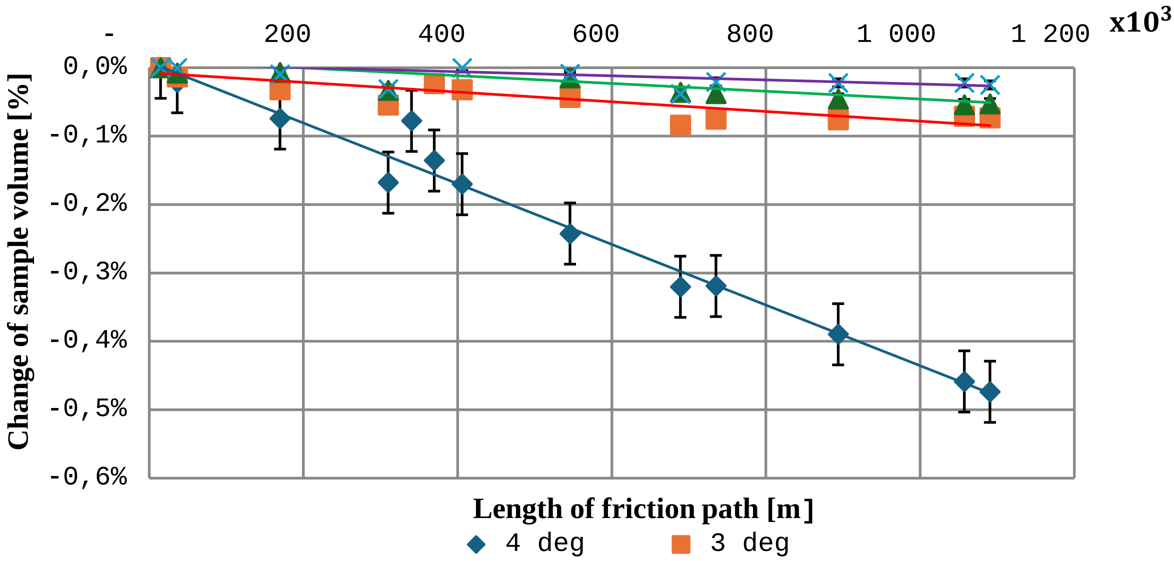

Fig. 4. Linear approximation of sample wear results on the friction path for a linear speed of 4.3 m/s

The results of sample wear measurements for a steel drum linear speed of 4.3 m/s (Fig. 4) show slight changes in sample diameters for skew angles of 1, 2 and 3°. The approximation curves for the relative change in diameters are inclined to the horizontal axis to a similar, slight degree. The greatest change in sample diameter can be observed for the sample with a skew angle of 4° - the reduction in sample diameter after the test was 0.5%. The total friction distance for samples rolling on the counter sample at a linear speed of 4.3 m/s was approximately 1100 km.

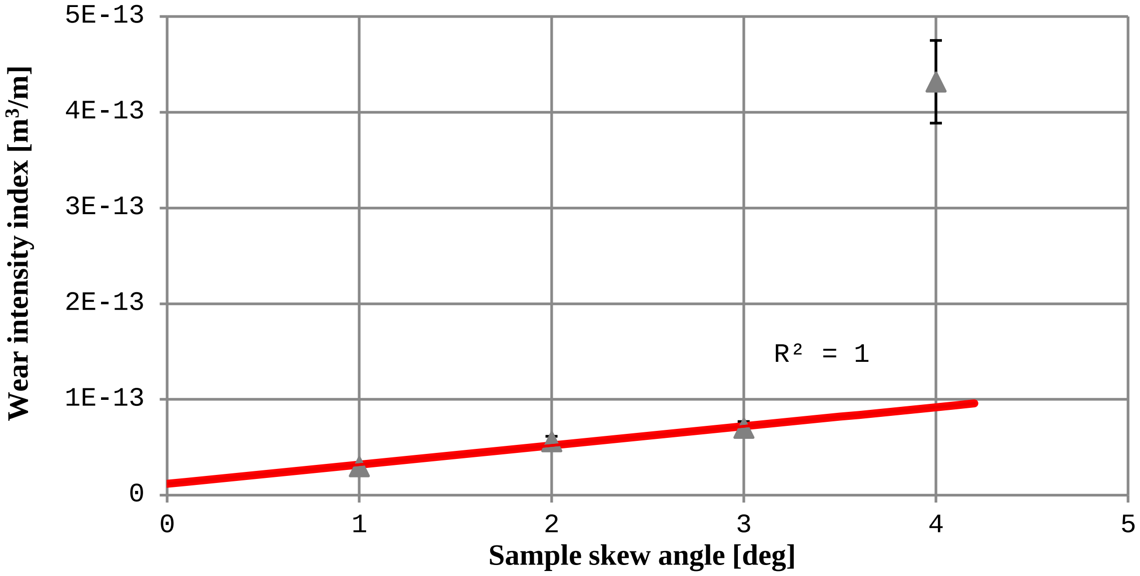

Fig. 5. Wear intensity index graph for measurements at a linear speed of 4.3 m/s

Fig. 5. shows the wear intensity index (I_z), which is a measure of the wear rate of the sample and approximation for skew angles of 1°,2° and 3°. I_z is defined (1) as sample wear (Z) relative to the friction path length (L), which is the product of the number of revolutions of the steel drum (L_{cB}) and its circumference ($D_B*\pi$):

$$I_z = \frac{Z}{L} = \frac{Z}{L_{cB} * D_B * \pi} \qquad \left[\frac{m^3}{m}\right] \tag{1}$$

The wear intensity index graph for a drum linear speed of 4.3 m/s (Fig. 5) shows slight or minimal wear of samples with skew angles of 1, 2 and 3 °. However, for the sample with a skew angle of 4°, a significant increase in the wear intensity index can be observed, deviating from the linear trend for samples with skew angles of 1, 2 and 3°. When comparing the value of the index for the sample with a skew angle of 4° with the index for a skew angle of 1°, this is an approximately tenfold increase. Skewing cylindrical samples at an angle of 4° leads to accelerated wear of the rolling surface of the samples, a reduction in its volume, and thus an increase in the impact of abrasive wear on the rolling surfaces of the cooperating elements.

Comparison of the rolling surfaces of samples with skew angles of 1° and 4° was presented in Fig. 6 below.

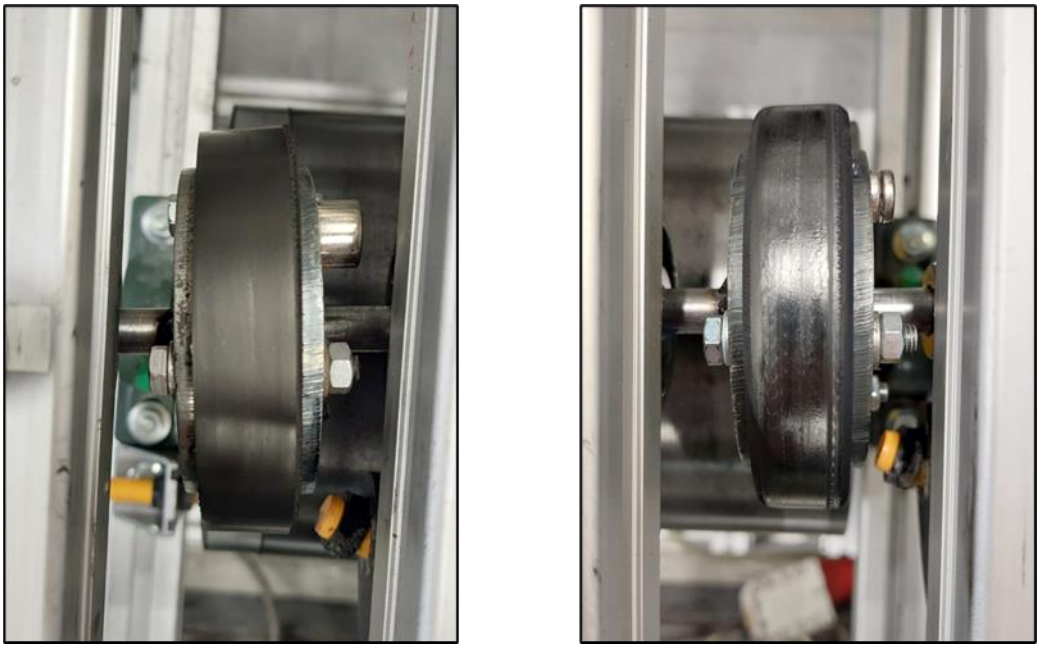

Fig. 6. Comparison of the rolling surfaces of samples with skew angles of 1° (left) and 4° (right)

As part of an attempt to forecast the wear intensity index for the friction work, reflecting the interaction between the roller and the conveyor belt, the results were approximated. Based on the index (I_Z) results for skew angles of 1°, 2°, 3° and 4° and linear sample speeds of 2.1 m/s, 3.2 m/s and 4.3 m/s, the average values of the wear intensity index (I_Z) were calculated for each angle. Next, a script was developed to approximate the points obtained with a spline function. The result of the approximation was function (2) describing the change in the wear intensity index "f" along with the skew angle.

$$f = a_0 + a_1 * \alpha + (\alpha > \alpha_0) * [c_1 * (\alpha - \alpha_0) + c_2 * (\alpha - \alpha_0)^2 + c_3 * (\alpha - \alpha_0)^3] \tag{2}$$

where:

α – sample skew angle [deg],

α_0 – designated argument of the function (threshold value) [deg],

a_0 = 1,93E-14, a_1 = 2,98E-14, c_1 = -1,40E-14, c_2 = 1,18E-13, c_3 = 1,74E-13.

The approximation of the wear function is presented in the graph in Fig. 7. The designated argument of the function (α_0 = 3.1), for which it retains its smoothness and continuity, constitutes the boundary between the linear approximation and the cubic approximation (third-degree polynomial).

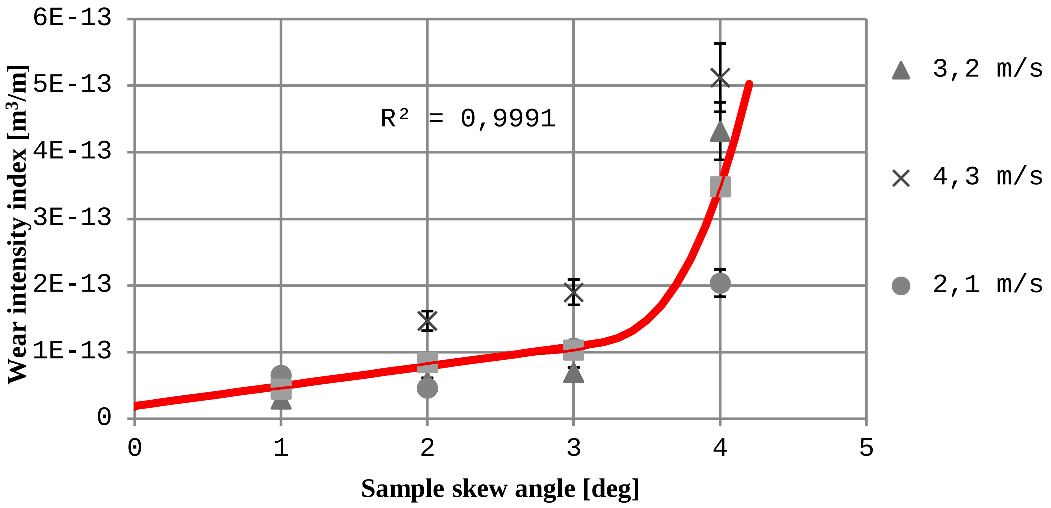

Fig. 7. Polynomial approximation of average values of the wear intensity index for measurements with three values of drum linear speed for samples of flame-retardant rubber

The fragment of the graph with linear approximation for skew angles of 1°, 2°, and 3° shows a linear increase in the wear intensity index. Above a skew angle of 3°, the approximation function takes the form of a third-degree polynomial and there is a significant increase in the wear intensity index.

3.2. Coefficient of friction

The wear of the rubber in the tested system depends on the coefficient of friction. With minor modifications (Fig. 8), the test rig allows this coefficient to be determined as a function of speed, skew angle and normal force load. The lateral force measuring system comprised a sample, a counter-sample, a loading weight and a dynamometer. The force was induced by controlled angular misalignment between the axes of the rolling elements. The lever mechanism was fixed to maintain a predefined skew angle, and the lateral force was recorded using the dynamometer.

Lateral force measurements were performed for three values of normal force acting on the sample (50 N, 80 N, 110 N) and for the most commonly used speeds in the operation of belt conveyors with advance roller sets (0.5–4.2 m/s). The effect of the skew angle was tested for the following values: 0.5°, 1°, 1.5°, 2°, 2.5°, 3°, 4° and 5°. Measurements were started at the lowest speed value in the range and then the speed was gradually increased. After reaching the next defined speed in the range, a measurement was taken. After the set measurement time for a single speed had elapsed, the speed was increased again. After measurements of the maximum set speed in the range, the linear speed of the drum was reduced and measurements were taken again.

Publisher: **KOMAG Institute of Mining Technology, Poland**

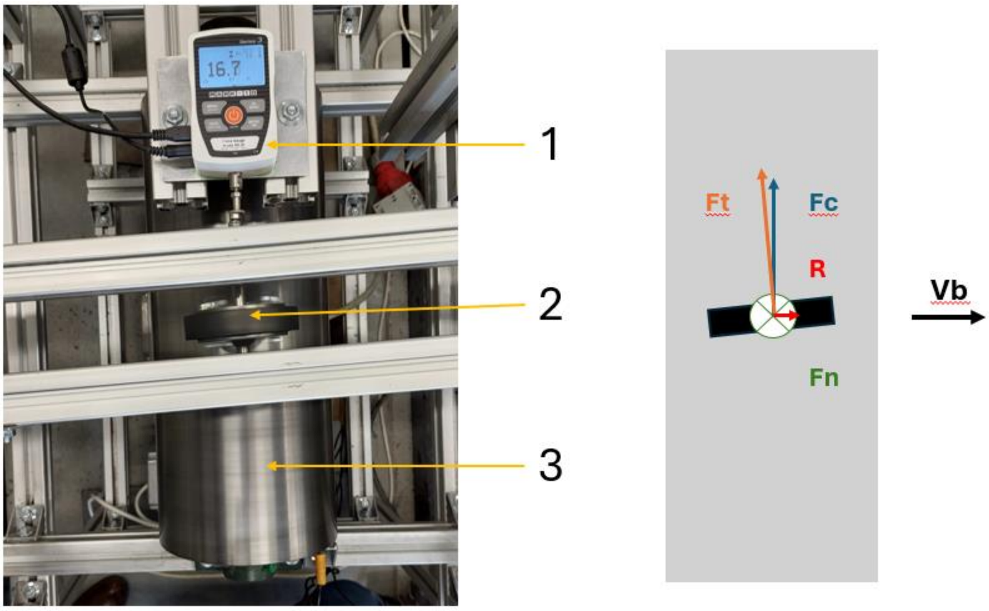

Fig. 8. Measuring system for testing lateral force on the left (1 – dynamometer, 2 – rubber sample, 3 – steel roller – counter sample) and vector diagram of the frictional forces between the sample and counter sample of the right (Fn – normal force, Ft – friction force, Fc – centring force, R – resistance force, Vb – counter sample speed)

The results of the measurements are presented in Fig. 9 below.

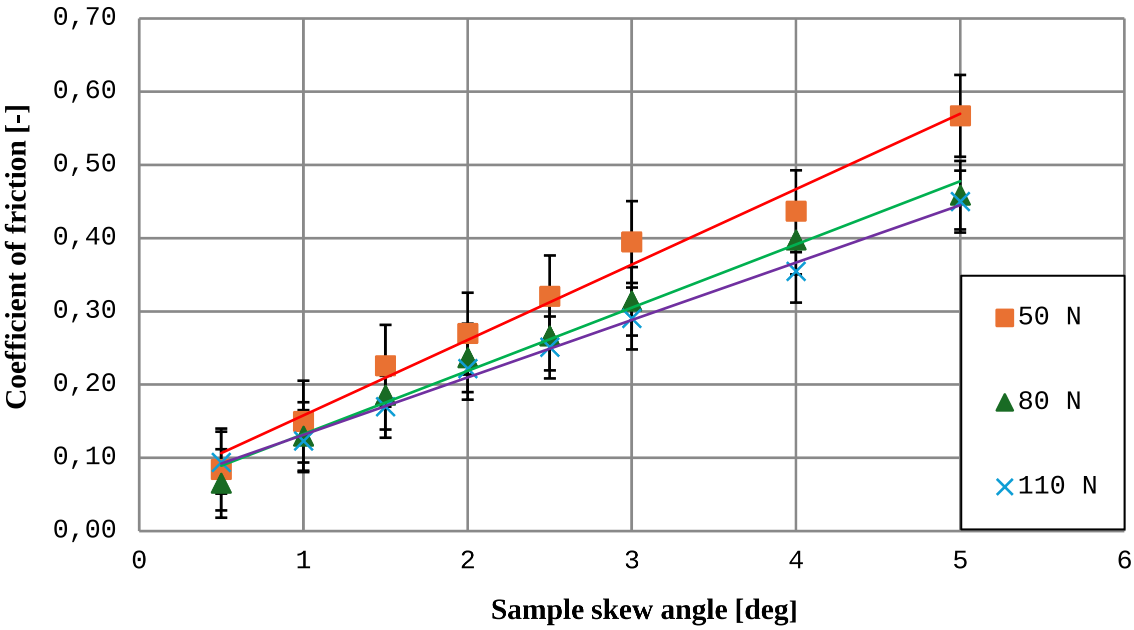

Fig. 9. Experimentally determined values of the coefficient of friction depending on the skew angle of the rubber sample for a linear drum speed of 2.1 m/s

Due to the lateral force values obtained as a result of the measurements, the friction coefficient values for the friction pair – a rubber sample and a steel drum – were determined. Using the definition of friction force (F_T) and taking into account the influence of the skew angle (α) on the direction of the centring force, the friction coefficient μ was calculated:

Publisher: **KOMAG Institute of Mining Technology, Poland**

$$\mu = \frac{F_C}{F_N * \cos(\alpha)} \tag{3}$$

where:
F_C – determined value of centring force [N],

F_N – value of normal force load [N],

α – skew angle of the sample [°].

The value of the normal force was applied gravitationally and remained constant throughout the test. The coefficient of friction was not monitored as a function of time. The contact temperature of the sample was measured and did not exceed 32°C.

The experimentally determined friction coefficient functions depending on the skew angle of rubber samples for three normal force load scenarios (50 N, 80 N, 110 N) and a linear drum speed of 2.1 m/s showed an approximately linear relationship (Fig. 9). For the analysed data, the highest friction coefficient value was found for a normal force load of 50 N on the samples. Lower values were obtained for a load of 80 N and the lowest for a load of 110 N. This leads to the conclusion that there is a relationship between a lower friction coefficient and an increase in load for the friction interaction between rubber and steel materials. The nature of the changes in the friction coefficient coincides with the results of experimental studies conducted on the friction interaction between a roller and a conveyor belt, published in [2].

4. Discussion

In order to measure the wear of rubber samples, a proprietary method was developed based on the number of revolutions performed, which allowed for precise determination of the volume loss of the sample material. The accuracy of the measurement obtained, amounting to 3%, was sufficient for the purposes of the planned tests. The measurement error can be reduced by significantly extending the test time. This method proved to be more accurate than the classic measurements using laboratory scales. In addition, the method allowed long-term testing of four samples with different skew angles at the same time and under the same conditions, without the need to interrupt the tests and dismantle the samples, significantly reduced the impact of external factors and measurement errors.

The results of the tests confirm that the stand allows for analysis of the wear of cylindrical samples made of rubber, determination of the wear intensity index (I_Z) depending on the skew angle and normal force load, and determination of the maximum skew angle of the roller under laboratory conditions, ensuring the centring of the conveyor belt, beyond which accelerated wear of the rubber in the roller-conveyor belt friction pair will occur.

For flame-resistant rubber samples, it was observed that the lowest wear occurred at skew angles of 1 ° to 3°, while the highest wear intensity values occurred at an angle of 4°, regardless of the linear speed of the steel drum. The results obtained indicate that under the test conditions, it was not the slip speed that was the dominant factor that influenced wear, but the skew angle of the samples. The tests showed that at skew angles above the limit value of 3°, the transverse forces that occur can lead to significant deformation of the samples and intensive increase in wear.

In addition, the laboratory test results demonstrate the wide research capabilities of the station in testing the friction parameters of the roller-conveyor belt friction pair. The results obtained indicate an increase in the lateral force acting on the samples with an increase in the skew angle and normal force, as well as a proportional increase in the friction coefficient with an increase in the skew angle. The lower the normal force acting on the samples, the higher the friction coefficient.

5. Conclusions

As part of the ongoing scientific and research project, a laboratory stand has been designed and built to test the friction cooperation between a roller and a conveyor belt. The test stand in the 'roller-roller' configuration consists of a support frame, lever systems and their bearings, systems for fixing and bearing samples made of rubber, and a driven steel drum.

The design of the test stand was developed in such a way as to enable stable and repeatable testing over a wide range of load and speed parameters. In the design of the test rig in the 'roller-roller' tribological system, the application of mechanical similarity theory and dimensional analysis methods was of significant importance, serving both as an engineering tool and as a theoretical basis for the research. They allowed for the proper selection of the test rig's operating parameters and justified the research assumptions, thus increasing the reliability and practical usefulness of the results obtained in the context of predicting the wear of consumable parts depending on the angle of the sample skew.

In view of further analyses and work on the wear of rubber used on conveyor belt covers in rubber – steel friction pairs, the research may be extended to include:

- Measurements of the wear intensity index for rubber with different properties, as well as other materials.
- Measurements of the wear intensity index for other kinematic and dynamic parameters.
- The possibility of conducting wear tests on samples aimed at creating theoretical wear models.

References

[1] Antoniak J.: *Przenośniki taśmowe: wprowadzenie do teorii i obliczenia*. Gliwice: Wydaw. Politechniki Śląskiej, 2004.

[2] Gładysiewicz L.: *Przenośniki taśmowe: teoria i obliczenia*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej, 2003.

[3] Antoniak J.: *Urządzenia i systemy Transportu Podziemnego w Kopalniach*. Katowice: Śląsk, 1990.

[4] Żur T., Hardygóra M.: *Przenośniki taśmowe w górnictwie*, 2. Wyd., Poprawione i Uzupeł. Katowice: Śląsk, 1996.

[5] Moore D. F.: „Friction and wear in rubbers and tyres", *Wear*, vol. 61, No 2, 1980, DOI: 10.1016/0043-1648(80)90291-4.

[6] Gehling T., Schieppati J., Balasooriya W., Kerschbaumer R. C., Pinter G.: „Fatigue Behavior of Elastomeric Components: A Review of the Key Factors of Rubber Formulation, Manufacturing, and Service Conditions", *Polymer Reviews*, vol. 63, No 3, pp. 763–804, 2023, DOI: 10.1080/15583724.2023.2166955.

[7] Schallamach A.: „How does rubber slide?", *Wear*, vol. 17, No 4, pp. 301–312, 1971, DOI: 10.1016/0043-1648(71)90033-0.

[8] Molnar W., Varga M., Braun P., Adam K., Badisch E.: „Correlation of rubber-based conveyor belt properties and abrasive wear rates under 2- and 3-body conditions", *Wear*, vol. 320, pp. 1–6, 2014, DOI: 10.1016/j.wear.2014.08.007.

[9] Uchiyama Y., Ishino Y.: „Pattern abrasion mechanism of rubber", *Wear*, vol. 158, No 1–2, pp. 141–155, 1992, DOI: 10.1016/0043-1648(92)90035-7.

[10] Karger-Kocsis J., Mousa A., Major Z., Békési N.: „Dry friction and sliding wear of EPDM rubbers against steel as a function of carbon black content", *Wear*, vol. 264, No 3–4, pp. 359–367, 2008, DOI: 10.1016/j.wear.2007.03.021.

[11] Dong C. L., Yuan C. Q., Bai X. Q., Yan X. P., Peng Z.: „Tribological properties of aged nitrile butadiene rubber under dry sliding conditions", *Wear*, vol. 322–323, pp. 226–237, 2015, DOI: 10.1016/j.wear.2014.11.010.

[12] Lorenz B., Persson B. N. J., Fortunato G., Giustiniano M., Baldoni F.: „Rubber friction for tire tread compound on road surfaces", *J. Phys.: Condens. Matter*, vol. 25, No 9, pp. 095007, 2013, DOI: 10.1088/0953-8984/25/9/095007.

[13] Cao J. *et al.*: „The study of wear particle emissions of soft rubber on rolling contact under braking conditions", *Wear*, vol. 506–507, pp. 204431, 2022, DOI: 10.1016/j.wear.2022.204431.

[14] Capanidis D., Kowalewski P., Leśniewski T., Paszkowski M., Wieleba W.: „Rola badań tribologicznych w aspekcie zwiększania trwałości i niezawodności eksploatacyjnej maszyn i urządzeń użytkowanych w Zagłębiu Miedziowym", *Zeszyty Naukowe Dolnośląskiej Wyższej Szkoły Przedsiębiorczości i Techniki. Studia z Nauk Technicznych*, t. 4, s. 47–64, 2015.

[15] Rowe K. G., Bennett A. I., Sawyer W. G.: „Traction and wear of an elastomer in combined rolling and sliding: Traction and Wear of an Elastomer in Combined Rolling and Sliding", *Lubr. Sci.*, vol. 28, No 2, pp. 97–106, 2016, DOI: 10.1002/ls.1303.

[16] Schallamach A., Turner D. M.: „The wear of slipping wheels", *Wear*, vol. 3, No 1, pp. 1–25, 1960, DOI: 10.1016/0043-1648(60)90172-1.

[17] Jensen J. S. K., Aghababaei R.: „Experimental investigation of three-body wear for rubber seals in abrasive slurry environment", *Wear*, vol. 534–535, pp. 205131, 2023, DOI: 10.1016/j.wear.2023.205131.

[18] Lawrowski Z.: *Tribologia: tarcie, zużywanie i smarowanie*. Wrocław: Oficyna Wydawnicza Politechniki Wrocławskiej, 2008.

[19] Siedow I.: *Analiza wymiarowa i teoria podobieństwa w mechanice*. Wydawnictwa Naukowo-Techniczne, 1968.

[20] Barenblatt G. I.: *Scaling, self-similarity, and intermediate asymptotics*. Cambridge texts in applied mathematics, No 14. Cambridge; New York: Cambridge University Press, 1996.

[21] Muller L.: *Teoria podobieństwa mechanicznego*. Wydawnictwa Naukowo-Techniczne, 1961.

[22] Bortnowski P., Kawalec W., Król R., Ozdoba M.: „Types and causes of damage to the conveyor belt – Review, classification and mutual relations", *Engineering Failure Analysis*, vol. 140, pp. 106520, 2022, DOI: 10.1016/j.engfailanal.2022.106520.

[23] Johnson K. L.: *Contact Mechanics*, Cambridge University Press, 1985. DOI: 10.1017/CBO9781139171731.

[24] Popov V. L.: *Contact mechanics and friction: physical principles and applications*, English ed. Heidelberg; New York: Springer, 2010.

[25] Kalker J. J.: *Three-Dimensional Elastic Bodies in Rolling Contact*, t. 2. w Solid Mechanics and Its Applications, vol. 2. Dordrecht: Springer Netherlands, 1990. DOI: 10.1007/978-94-015-7889-9.

[26] Faustmann C., Bajzek M., Hick H., Edtmayer J., Walch S.: „System models and model classification in tribological system development", *Systems Engineering*, vol. 23, No 6, pp. 783–794, 2020, DOI: 10.1002/sys.21562.