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Experimental studies of truck transport brake pads materials friction properties

The work presents the results of experimental systematic studies of "wheel-brake pad" friction pairs wear resistance and the effect of the wear-resistant coating on the wear, in particular, from metal-ceramic friction materials (ФМК-8), carbon composite materials (ВВКМ) in comparison with carbon steel of grade 45. It was established that the instantaneous values of brake pads friction coefficients during the tests on inertial stand are random in nature and require the use of mathematical statistics methods for their analysis. Change nature in pads and wheels friction force instantaneous values is determined by pressing forces. It is shown that the mathematical expectation of the friction coefficients values is within the normalized permissible interval. The probability of friction coefficients instantaneous values matching into the normalized interval at a pressing force of 10kN is 0,6-0,8 for speeds up to 60 km/h, for the rest is more than 0,8 at pressing force of 20kN, the specified probability exceeds 0,85 for the entire range of speeds. With a pressing force of 20kN, the probability of values exceeding the normalized interval does not exceed 0,15, with a pressing force of 10kN, the friction coefficients exceeded the maximum normative values more than 0,35 for speeds up to 40 km/h. It has been established that the most wear-resistant pads are coated with metal-ceramic material (ФМК-8) and carbon-carbon composite materials (ВВКМ). It is shown that the described technique based on the mathematical statistic application allows to perform more in-depth analysis of freight wheeled road trains brake pads frictional properties.

Keywords: *mathematical statistics, friction, destruction, friction materials, friction pairs wear resistance.*

Introduction. In modern period of development of industry manufacture of Ukraine, the problem of basic foundations creation for transport equipment development has arisen. It concerns, in particular, issues of friction and wear in transport machines. The relevance is due to the fact that the current state of technology development is characterized by strict conditions of the most diverse transport systems operation, which is associated with an increase in specific loads due to increase in capacities; speeds; by the action of complex static cyclic and dynamic loads; under the impact of various corrosive-active environments as well as temperature [1-3]. It is known from operational practice that 70-80% of disruptions in normal functioning or complete failure of technical systems are caused by the failure of tribosystems elements due to surface destruction as a result of wear and tear and other accompanying processes - fretting erosion, etc. Therefore, increasing the friction units durability was and remains one of the most important technical problems of modern times in terms of reliability increasing and service life extending for transport vehicles [4-7]. However, despite the large volume of publications on this topic, it can be noted that the diversity, large volume of experimental material and often uncertainty and contradiction of information regarding the tribological properties of the material [8, 9] involved in friction and wear pairs leads to the need to find an additional resource in increasing the wear resistance properties of brake pads material, in particular of transport trucks [10, 11].

Therefore, we provided additional research on brake pads frictional properties in the conditions of experimental stands, which were as close as possible to the real kinematic and dynamic conditions of transport trucks operation.

Research purpose and task is to provide systematic experimental studies of brake pads frictional properties made of different materials.

Research Materials and Methods. Special stand shown in Figure 1 was used in the experiments. Express tests on dry friction were carried out for brake pads material selection (possible case of braking wheel pair operation in the dry friction mode was simulated on the stand) together with specialists of Powder Metallurgy, SPA (Belarus) and the Institute of Electric Welding named after Ye. O. Paton of the National Academy of Sciences. Pads samples with coatings testing for wear resistance during dry friction was carried out for 45 minutes at a specific pressure of 0.6 MPa and a counterbody rotation frequency of 80min^{-1}, the counterbody was a disc made of hardened steel 40XH. Carbon structural high-quality steel 45 was used as a reference sample of brake pads. Pads were made of two types: ФМК-8 metal-ceramic friction (iron-based), "carbon-carbon" composite materials ВВКМ. In the first case, the main characteristics that were subject to registration were determined, in particular: wheel rotation linear speed; time from the start of braking to complete stop of the wheel; instantaneous value of pad pressing force on the wheel; instantaneous value of friction force; wheel heating temperature.

The results of experimental studies are shown in Figures 1-10.

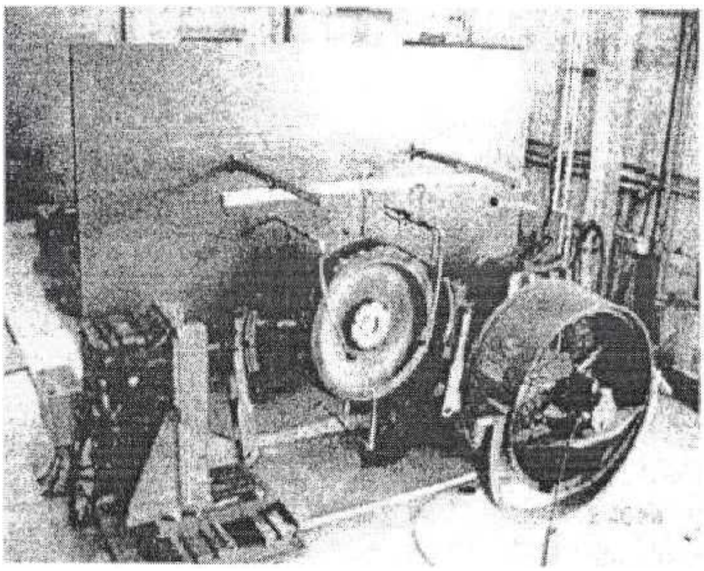

Fig. 1. **Stand for Determining the Frictional Properties of Brake Pads**

The instantaneous friction coefficient is defined as instantaneous value of the friction force to instantaneous value of the pressing force ratio. It was established that the registered parameters are random values, so their processing requires the use of statistical methods of analysis.

Pressing forces, friction forces and friction coefficients changes during braking data analysis (Fig. 2) shows that the instantaneous values of pressing forces change according to the harmonic law relative to the average nominal value, while the change in friction forces has a deterministic nature.

Decisive factor affecting the nature of change in the instantaneous values of friction coefficients is the pressing force (Fig. 2), therefore it is appropriate to determine the instantaneous values of friction coefficients as instantaneous values of friction force to nominal (average) value of pressing force ratio.

For statistical processing, the entire set of measured parameters was divided into separate arrays according to fixed braking speeds with an interval of 5km/h, while the initial speed was 20km/h [12, 13].

As a statistical law of pad pressing the wheel force distribution, the normal distribution law was adopted, for which the distribution function and probability density have the form:

$$F(\mathrm{x}) = \frac{1}{\sqrt{2\cdot\pi\cdot\sigma}} \int_{-\infty}^{\mathrm{x}} \mathrm{e}^{\frac{(\mathrm{x}-\mathrm{a})^2}{2\cdot\sigma^2}} dx \tag{1}$$

$$\varphi(x) = \frac{1}{\sqrt{2\cdot\pi\cdot\sigma}} \cdot e^{\frac{(x-a)^2}{2\cdot\sigma^2}} \tag{2}$$

where α and σ^2 - are the mathematical expectation and variance of the random variable *x*.

Confidence intervals for mathematical expectation were determined by the formula:

$$\bar{x} - z_{p1} \cdot \frac{\sigma}{\sqrt{n-1}} < a < \bar{x} - z_{p2} \cdot \frac{\sigma}{\sqrt{n-1}} \ , \tag{3}$$

where $\bar{x}$ – is sample average of n independent values;
z_{p1} - is the quantile of the normalized normal distribution

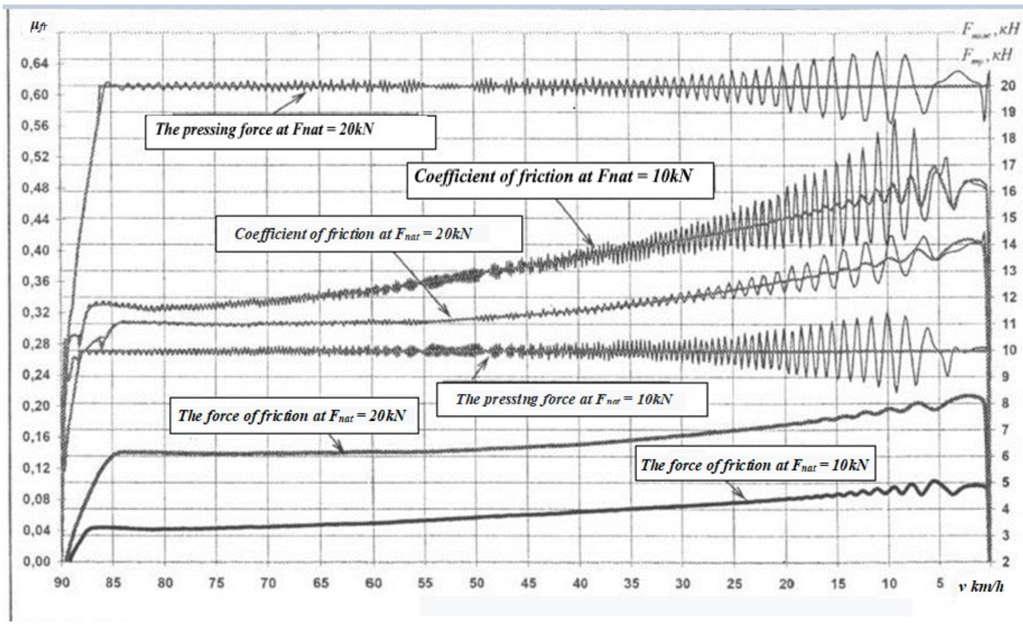

Fig. 2. **Processes of changes in registered parameters during braking with an initial speed of 80km/h.**

Probability distribution densities of instantaneous friction coefficients (Figs. 3, 4) show that their value increases as the rate of dispersion of changes decreases. The instability of the friction coefficient at low speeds of wheel rotation can be due to the impact of the temperature of both the wheel itself and the brake pad, however, this statement requires experimental confirmation, since during tests on an inertial stand, the temperature is measured only on the wheel.

Despite the fact that the average values of friction coefficients (Figs. 5, 6) are in the given normalized range of permissible values of friction coefficients [14], nevertheless, in order to evaluate the braking properties of experimental pads, it is necessary to take into account the probability that the instantaneous value of the friction coefficient will be within the permissible range ($[\mu(v)]_{min}$, $[\mu(v)]_{max}$).

Probability of random value is equal to the integral of probability density within these limits [15]:

$$P(\mu \geq [\mu(v)]_{max}) = \int_{\mu_1}^{\infty} p(\mu) \cdot d\mu = 1 - F([\mu(v)]_{max}), \tag{4}$$

where $[\mu(v)]_{min}$,$[\mu(v)]_{max}$ are, respectively, minimum and maximum normalized values of friction coefficients established [15] for speed v.

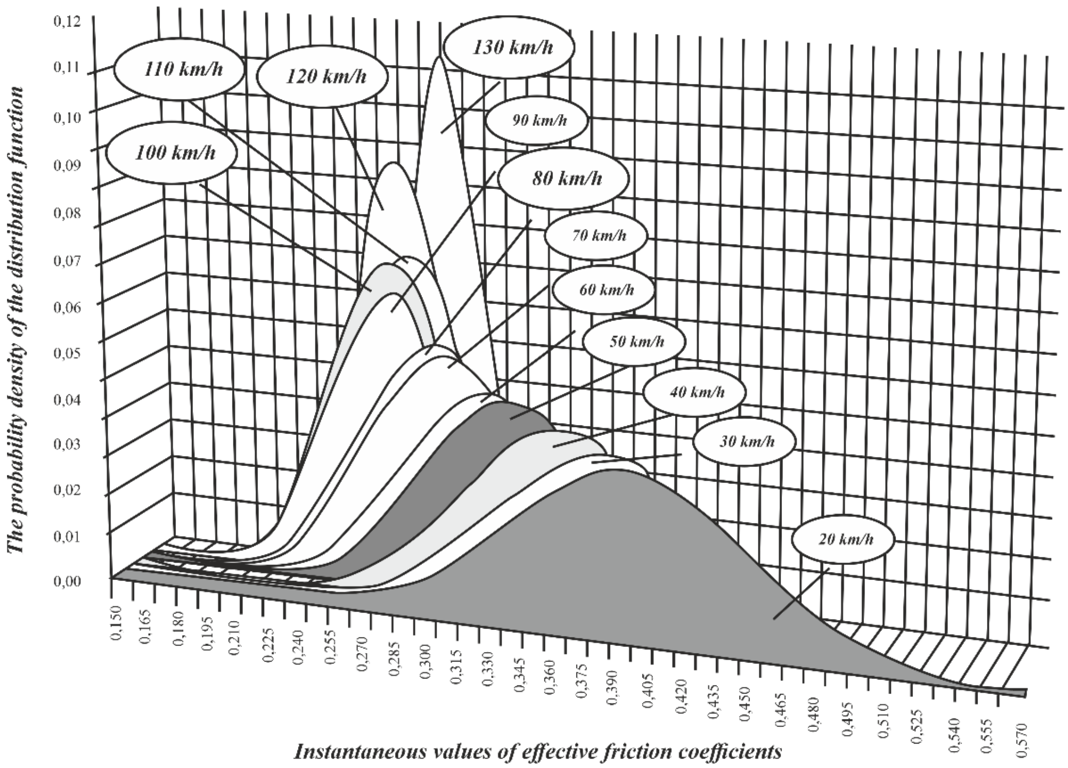

Fig. 3. **Density of Friction Coefficients Instantaneous Values Distribution at Pad Pressing the Wheel Force of 10kN.**

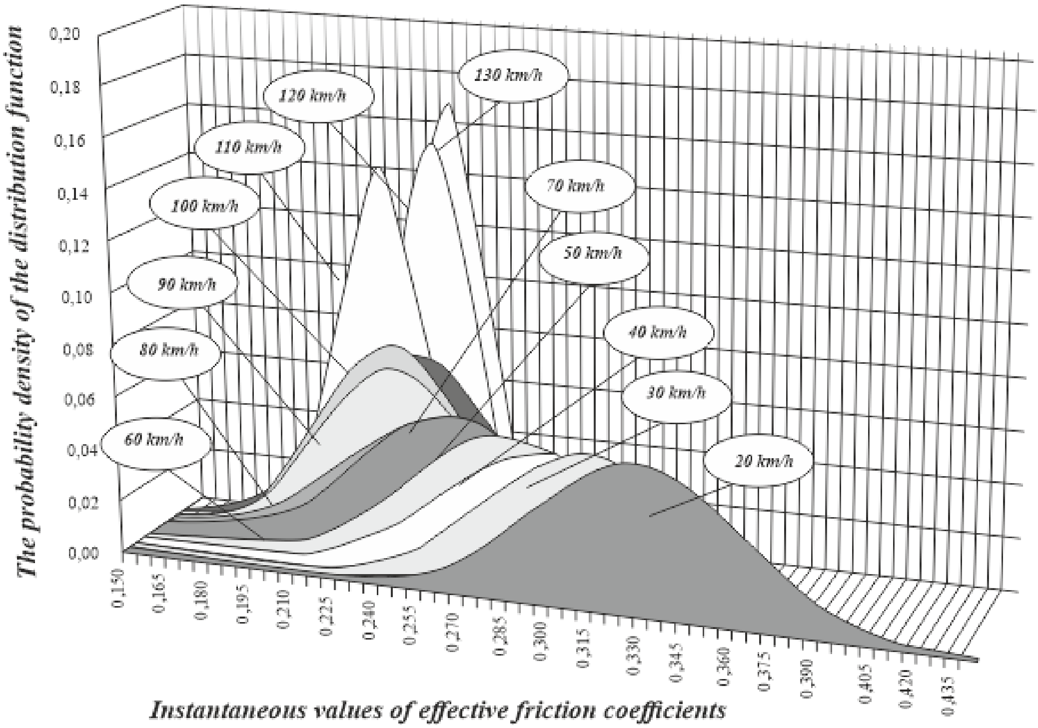

Fig. 4. **Density of Friction Coefficients Instantaneous Values Distribution at Pad Pressing the Wheel Force of 20kN**

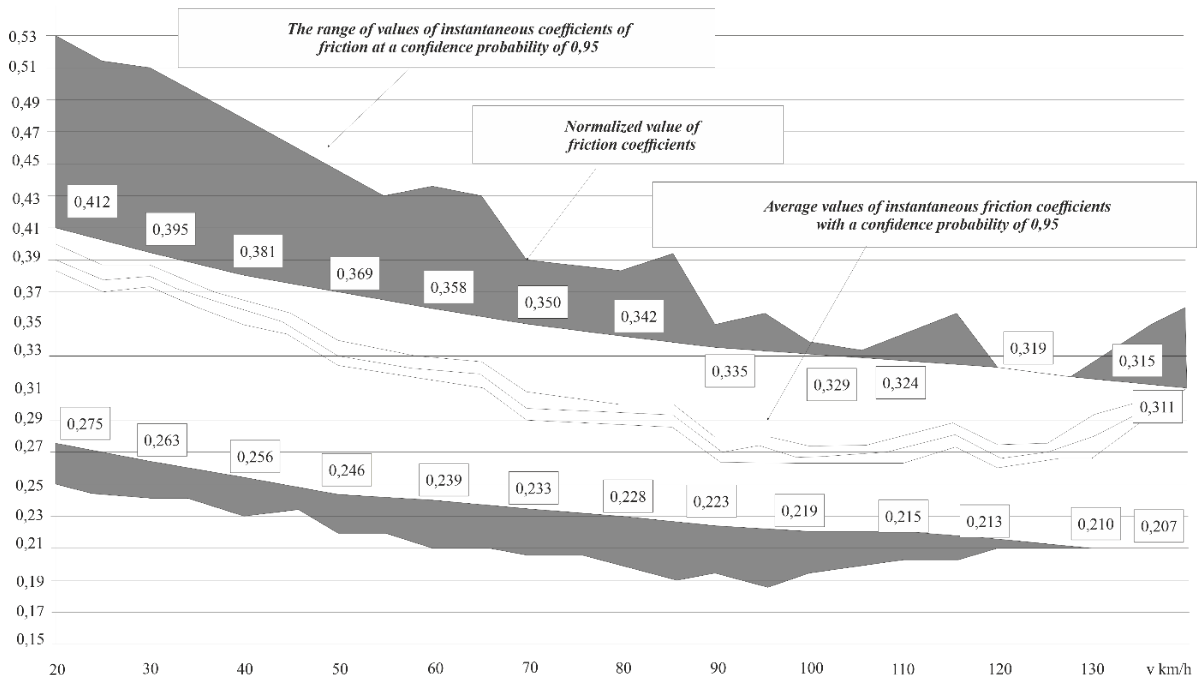

Fig. 5. **Friction Coefficients Average Values at Pad Pressing the Wheel Force of 10kN**

The performed calculations showed that the probability of friction coefficients instantaneous values matching into the normalized interval [14] at a pressing force of 10kN is 0,6-0,8 for speeds up to 60km/h, for the rest is more than 0,8 at pressing force of 20kN, the specified probability exceeds 0,85 for the entire range of speeds.

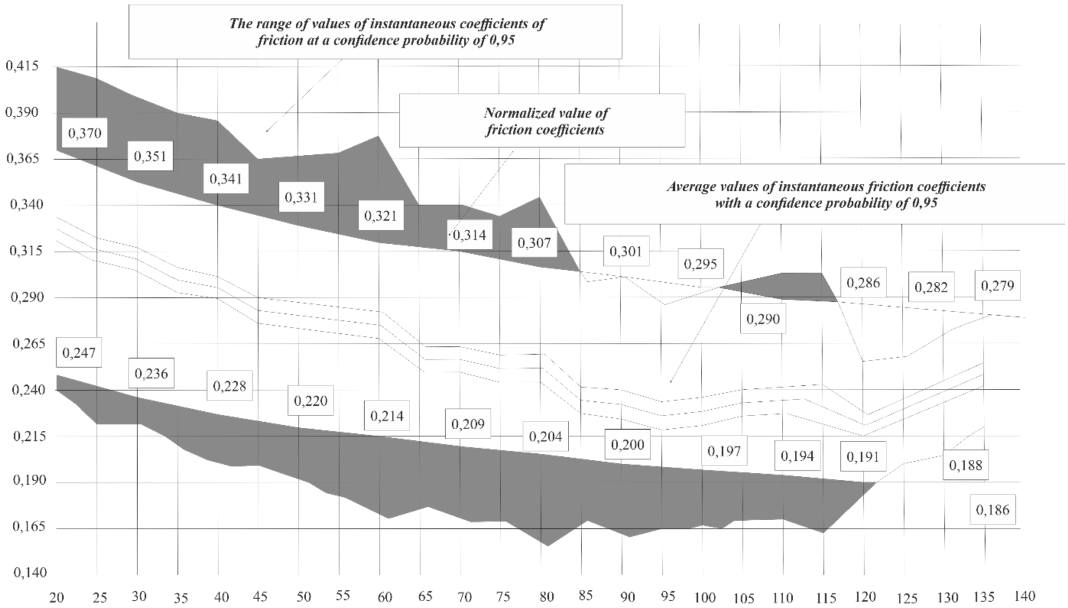

Fig. 6. **Friction Coefficients Average Values at Pad Pressing the Wheel Force of 20kN**

When analyzing the friction properties of a brake pad, it is necessary to analyze the maximum and minimum values of friction coefficients, since high friction coefficients can lead to damage to the surface of wheel pairs during braking, and low ones - to insufficient braking efficiency of a truck. The probability of the pad friction coefficients exceeding the maximum normalized value is determined by formula (5)[2], and the probability that the friction coefficients will be below the minimum normalized value is determined by formula (6) [2]

$$P(\mu \geq [\mu(\mathrm{v})]_{max}) = \int_{\mu_1}^{\infty} p(\mu) \cdot d\mu = 1 - F([\mu(\mathrm{v})]_{max}) \tag{5}$$

$$P(\mu \leq [\mu(\mathrm{v})]_{min}) = \int_{-\infty}^{\mu_1} p(\mu) \cdot d\mu = F([\mu(\mathrm{v})]_{min}) \tag{6}$$

Calculation studies show that with a pressing force of 20kN, the probability of the values of friction coefficients exceeding the normalized interval does not exceed 0,15, and with a pressing force of 10kN, the probability of the friction coefficients exceeding the normative values for speeds up to 40km/h inclusive is more than 0,35.

The high probability of the friction coefficients exceeding the maximum normative values at a pressing force of 10kN requires an analysis to be carried out under the condition of preventing a sliding situation. As a criterion, the limit coefficient of wheels adhesion with asphalt was used. Results of the calculation showed that the maximum probability of slipping is 0,55, that is, it should be expected that out of a hundred cars operated on experimental composite pads, only five vehicles can have a slip on wheel pairs.

Friction coefficients instantaneous values coefficients of variation (range) which are defined as standard deviation to the mathematical expectation ratio, show that with a pressing force of 10kN, the maximum values of the coefficients of variation correspond to speeds up to and including 40km/h, and with a pressing force of 20kN - the range of rates (60-80) km/h

In the second part of the experiments, samples wear resistance was assessed by the weight method. All samples were pre-treated before testing.

Experiments results showed that the brake pads made of metal-ceramic materials have the highest wear resistance, and it was noticed that the wear resistance increases with a decrease in the fraction of material used. These data are in good agreement with the results known from the literature, where it is recommended to use finely dispersed powders - fractions less than 20µm in order to obtain high-quality wear-resistant coatings from ceramic materials. The tests were carried out on the MI-IM friction machine with a special device for introducing a friction pair of abrasive suspended in lubricant to the point of contact. A lubricant-abrasive mixture was used, which consisted of industrial lubricant И-20 and 2% boron carbide, with a grain size of 4-5µm. The test mode was as follows: friction speed 0,7-1,0 m/s; pressure in the friction pair 2-3 MPa; friction path during one cycle is 3-7km; cycle duration 1-1,5 hours. Wear was determined using I3B-1 length gauge with 1µm divisions in two mutually perpendicular planes along two sections. The insert that was worn was measured in the central plane along two sections.

The intensity of wear during the set period was estimated by the formula:

$$I_O = \frac{I_{sw}}{I_{fp}}, \qquad (7)$$

where I_{sw} - is wear of the sample in diameter, µm;
I_{fp} - is friction path during the test period, km.

The friction path during the test period is determined by the formula:

$$I_{fp} = \pi \cdot D \cdot N \cdot 10^{-6}, \qquad (8)$$

where D - is the sample diameter, mm;
N - is the rotation frequency of the sample, min.$^{-1}$.

During the test, the moment of friction of the "wheel - counterbody" pair was determined on the scale of the registration mechanism after every ten minutes of testing.

Friction coefficient was determined by the moment of friction and the applied load

$$\mu = \frac{M_{mf}}{(R_{sr} \cdot P)}, \qquad (9)$$

where M_{mf} - is the moment of friction;
R_{sr} - is sample radius;
P - is applied load.

Test results analysis (Fig. 7-10, designations for figures are the same) shows that the wear resistance of the coating made of metal-ceramic powder (fraction 14 µm) is higher than the wear resistance of the coatings made of powder "carbon-carbon" composite materials and the wear resistance of samples made of steel 45. In the process of samples with coatings wear, the phenomenon of salting the coatings was observed, i.e. wear gradually decreased after a certain time after the tests beginning. At the same time, the friction pair accretion period was about 1 hour on average. The end of accretion process was estimated by the moment of friction and wear stabilization (Fig. 10).

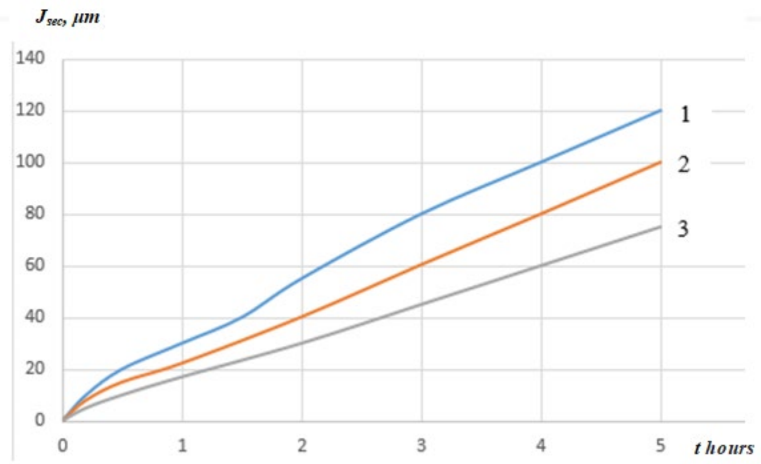

Fig. 7. **Graphs of sample wear dependence on test intensity:**
1 - reference sample made of steel 45; 2 - sample from ВВКМ; 3- sample from ФМК-8.

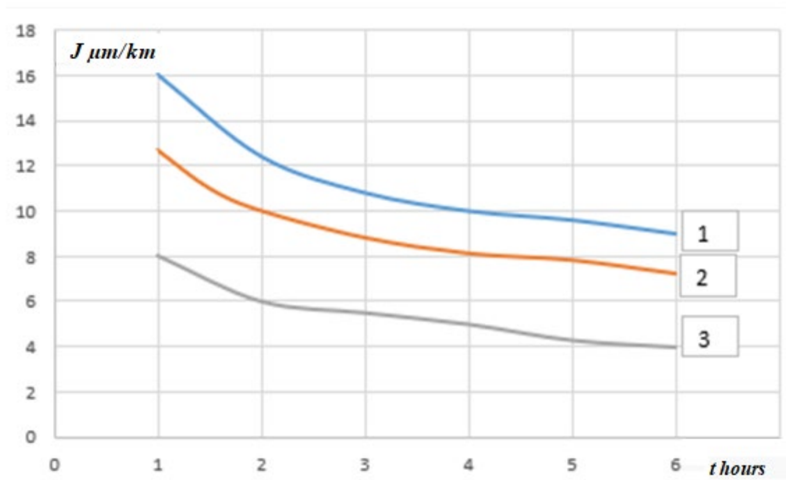

Fig. 8. **Graphs of Wear Intensity Dependance on Tests Duration.**

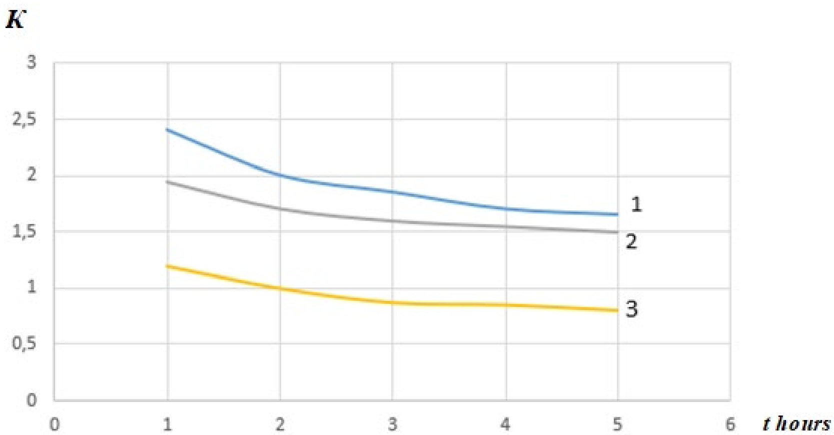

Fig. 9. **Graphs of the dependence of the wear coefficient K on the duration of the tests.**

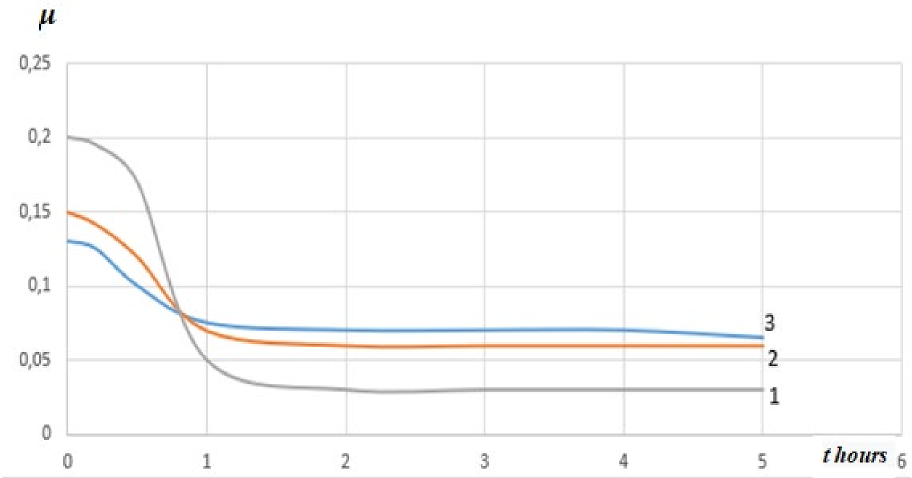

Fig. 10. **Graphs of Friction Coefficient Dependence on Tests Duration.**

Conclusions

1. It was established that the instantaneous values of brake pads friction coefficients during the tests on inertial stand are random in nature and require the use of mathematical statistics methods for their analysis. Change nature in pads and wheels friction force instantaneous values is determined by pressing forces.

2. It is shown that the mathematical expectation of the friction coefficients values is within the normalized permissible interval. The probability of friction coefficients instantaneous values matching into the normalized interval at a pressing force of 10kN is 0,6-0,8 for speeds up to 60 km/h, for the rest is more than 0,8 at pressing force of 20kN, the specified probability exceeds 0,85 for the entire range of speeds.

3. With a pressing force of 20kN, the probability of values exceeding the normalized interval does not exceed 0,15, with a pressing force of 10kN, the friction coefficients exceeded the maximum normative values more than 0.35 for speeds up to 40 km/h. The maximum probability of slipping corresponds to a speed of 30 km/h with a pressing force of 10kN and is 0,55. At the same time, the variation coefficient at a pressing force of 10kN corresponds to the speed range of (20-40) km/h, and at a pressing force of 20kN - (60-80) km/h.

4. It has been established that the most wear-resistant pads are coated with metal-ceramic material (ФМК-8) and carbon-carbon composite materials (ВВКМ).

5. It is shown that the described technique based on the mathematical statistic application allows to perform more in-depth analysis of freight wheeled road trains brake pads frictional properties.

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Експериментальні дослідження фрикційних властивостей матеріалів гальмівних колодок вантажного транспорту

В роботі наведені результати експериментальних системних досліджень зносостійкості пар тертя “колесо-гальмівна колодка” і вплив на зношування зносостійкого покриття, зокрема з металокерамічних фрикційних матеріалів (ФМК-8) вуглецевих композитних матеріалів ВВКМ в порівнянні з вуглецевою сталлю марки 45. Встановлено, що миттєві значення коефіцієнтів тертя гальмівних колодок при випробуваннях на інерційному стенді мають випадкових характер і вимагають для свого аналізу застосування методів математичної статистики. На характер зміни миттєвих значень сили тертя колодок і коліс визначаючий вплив здійснюють сили натискання. Показано, що математичне сподівання значень коефіцієнтів тертя знаходиться в межах нормованого допустимого інтервалу. Імовірність попадання миттєвих значень коефіцієнтів тертя в нормований інтервал при силі натискання 10кН складає для *швидкостей до 60км/год, 0,6-0,8 для решти – більше 0,8 при силі натискання 20кН, вказана імовірність перевищує 0,85 для всього діапазону швидкостей. При силі натискання 20кН імовірність виходу значень за нормований інтервал не перевищує 0,15, при силі натискання 10кН перевищення коефіцієнта тертя максимальних нормативних значень для швидкостей до 40км/год складає більше 0,35. Встановлено, що найбільшою зносостійкістю володіють покриття колодок з металокерамічного матеріалу (ФМК-8) і вуглець-вуглецеві композитні матеріали (ВВКМ). Показано що викладена методика на основі застосування апарату математичної статистики дозволяє проводити більш глибокий аналіз фрикційних властивостей гальмівних колодок вантажних колісних автопоїздів.*

Ключові слова: *математична статистика, тертя, руйнування, фрикційні матеріали, зносостійкість пар тертя.*