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EVALUATION OF THE INFLUENCE OF THE PERCENTAGE OF COPPER CONTENT ON THE PHYSICAL AND CHEMICAL PROPERTIES OF THE FRICTION MATERIAL

Summary. Copper is one of the main components of friction materials used in vehicles' brake systems. It is mainly used due to two features: good thermal conductivity and lubricity. Unfortunately, it is harmful not only to humans but also more to aquatic life. For this reason, there is an attempt to minimize its use. This paper presents the results of testing four groups of samples with different Cu contents (5, 10, 15, and 20%). Laboratory tests were performed using calorimetry, hot wire method, and pin-on-disc method. This allowed to determine selected physico-chemical material properties of samples, which were then used for simulation studies. They were intended to check how the heating process of friction materials with a chemical composition such as made samples will proceed in real conditions, in real brake pads.

1. INTRODUCTION

Dynamic development of the industry obliges designers to focus more and more on the problem of increasing brake efficiency. This applies primarily to the automotive, but also to any other industry that uses friction materials. Due to the constantly growing number of motor vehicles on the roads and the related to this modernization of infrastructure, drivers are required to brake and accelerate their vehicles more often [1-2]. Through the constant research and innovative solutions of the composition of friction lining mixtures, engineers of leading brands give users the opportunity to choose different types of brake elements depending on the driving style or expectations [3]. There are many types of pad material mixtures on the market, most of which are trade secrets of a producer [4-5].

The difference in the composition of individual products can provide a shorter braking distance or better heat dissipation, unfortunately at the expense of shorter lifetime of the lining. A view on the on the brakes is presented in Fig. 1).

Brakes in motor vehicles are a very important component. They must work reliably and consistently throughout the entire life cycle, because health and even the lives of many people may depend on it. The correct selection of the kinematic friction pair, which in disc brakes is created by the disc and brake pads, has a very large effect on the aforementioned characteristics. In the vast majority of cases, the brake disc is made of cast iron. However, brake pad are much more complex parts. On average, they consist of about ten to twenty different materials. The latest technologies make it

possible to obtain materials of various composition and proportions, and to permanently combine them in fully controlled processes. The current research conducted worldwide includes aspects related to the properties of brake materials and their effect on the environment.

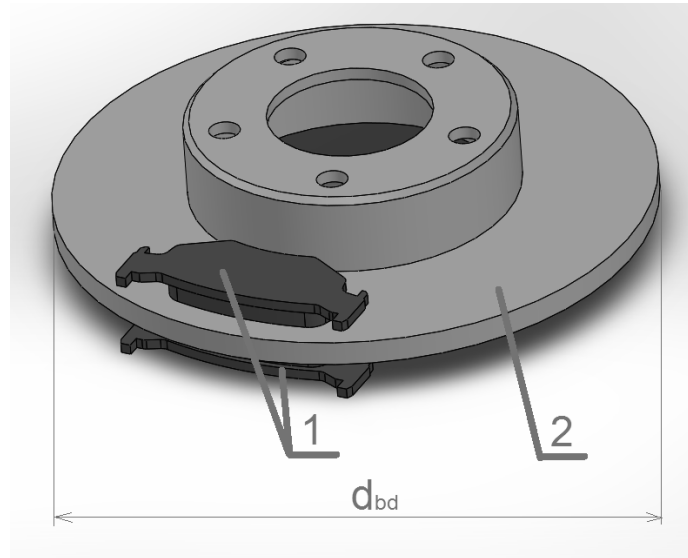


Fig. 1. View on the brakes: 1 – pads, 2 – disc, d_{bd} – external disc diameter

Environmental protection in the transport industry is very important. New production technology solutions, modern materials, and operating fluids are introduced, which are more friendly to living organisms and easier to utilize. This also applies to the latest brake materials.

One of the basic components of brake pads is copper. The influence of Cu on the properties of the friction material is strongly related to its percentage content [6]. The disadvantage of using copper is the change in coefficient of friction value along with the change in contact pressure and friction speed, which has been demonstrated by many researchers [7-9]. Changing coefficient of friction can also generate unwanted noise [10].

Copper, like cast iron, creates contact zones during friction. This is because, although it is a soft material, it is usually harder and more resistant to abrasion than the warp (which is usually resin). It forms a thin layer on the abrasive surface during abrasion, therefore increasing thermal conductivity and resistance to high temperatures [11].

For the production of friction materials, powdered copper with nano (50-200 nm) or micro (400-600 μm) particles is most often used [12]. However, there are proposals for using much larger particles - around 1-2 mm. The origin of such fractions may be different. For example, it was proposed that copper for the production of friction materials should be obtained from shredded windings of electric motors, which supports the recycling process [11].

Unfortunately, copper is harmful to people. Higher doses of copper may cause vomiting, and as a result of constant exposure, copper might lead to liver damage. At concentrations exceeding 3 mg / L, some people experience acute gastric irritation. In adults suffering from Wilson's disease, due to a disturbance in the mechanism regulating copper metabolism, its prolonged ingestion may lead to liver cirrhosis. In addition, a higher concentration of copper also results in major damage to aquatic life and causes changes in the taste and color of the water. [13]. Some countries have introduced regulations limiting the permissible fraction in brake pads [14-18]. Therefore, there is a need for a replacement material, which can be, e.g., a mixture of graphite and titanium. In addition, the material obtained in this way has a lower level of emitted noise arising during friction [10]. As literature sources show, much hope can be placed in the use of materials of, e.g., plant or animal origin [19 – 21]. They are currently widely used in transport. In the production of brake linings, as replacements for traditional materials, the most common are organic materials of plant (from leaves, stems or seeds) or animal (e.g. hair, fur). They are used as a matrix, i.e. a binder of all components of the pad. It must be

a substance that will be characterized by a high and stable coefficient of friction, resistance to high and rapidly changing temperatures, and low mass. The warp usually accounts for about 20% of the pad's volume [22]. It must also be a material that does not react with any other component of the pad, otherwise the composite could delaminate, which would significantly reduce the effectiveness of the braking system.

The problem is serious, because the number of vehicles traveling on the roads is spacious. One can venture to say that transport is the backbone of, among others, production or trade. In view of the aforementioned, any action taken to eliminate or at least reduce the level of pollution generated by transport is noteworthy.

The aim of the work is to check through a series of laboratory tests how the percentage content of copper affects the physical and chemical properties of prototype friction material samples with different percentage of copper. Then it is planned to perform simulation tests that will show how individual sample materials would work as a brake pad production material.

2. EXPERIMENTAL PROCEDURE

Before investigation, the test samples were made. The ingredients in the assumed proportions were mixed together in the mixer for 5 minutes. Prepared powder was poured into bolted forms. A high internal pressure was ensured. The whole was heated according to the resin manufacturer's instructions. Prepared samples were divided into 4 different groups. The basic difference between individual samples made is the volume content of copper (5-20%) and fillers (15-30%). The composition of samples is presented in Table 1.

The chemical composition was similar to the friction materials used in commercial brake pads, but the number of components was slightly smaller (in commercial friction materials, it is usually 15-20 different components, whereas the tested samples contained 9 substances). Another component is type of resin – in commercial friction material, there is usually phenolic resin, whereas in our case, epoxy resin was chosen. The genesis of this choice was easier accessibility and lower price. Samples will not work at high temperature; the potency of this binder seems sufficient then. Samples were cylindrical with the following dimensions: diameter - 25 mm and height - 10 mm. For each of the groups, two samples were produced for main research and two additional samples that were used to determine the parameters of the experiment (Fig. 2).



Fig. 2. Photograph of prepared cylindrical samples

Friction elements of braking systems are subjected to different types of wear. The most important is abrasive wear, in particular, the destruction of the top layer of cooperating moving parts. The material loss is caused by the separation of material particles due to scratches, micro-cutting, and fissuring.

The tests of physical properties were performed with the use of a T-11 pin-on-disc tribotester (Fig. 3). This method can be used both in dry friction tests and in the presence of various lubricants [23-24]. With the help of the environmental chamber, experiments can be carried out in the presence

of various gases or humidity [26-27]. The stand makes it possible to determine the average friction coefficient between a friction pair and to assess the wear rate of friction surfaces.

Table 1

Composition of samples

Component	1st group of samples	2nd group of samples	3rd group of samples	4th group of samples
1. Cu	5%	10%	15%	20%
2. S235JR (C-0.18%, P-0.4%, S-0.38%, N-0.005%)	7%	7%	7%	7%
3. Aramid	15%	15%	15%	15%
4. Epoxy resin	20%	20%	20%	20%
5. Graphite	7%	7%	7%	7%
6. MoS ₂	4%	4%	4%	4%
7. SiC	4%	4%	4%	4%
8. Powdered glass (SiO ₂ -70%, Na ₂ O-15%, CaO-10%, MgO+Al ₂ O ₃ +Fe ₂ O ₃ -5%)	5%	5%	5%	5%
9. Fly ash	30%	25%	20%	15%
10. Another filler	the rest - around 3%			

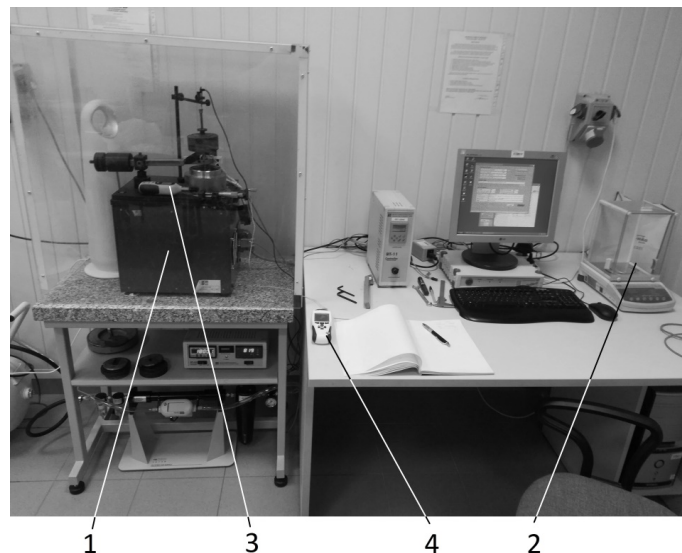


Fig. 3. Test station: 1 – T-11 tribological tester, 2 – Radwag WAS 160/C/2O scale, 3 – MT886 hygrometer, 4 – Velleman DEM106 temperature sensor

It is important that the spindle is positioned correctly at an angle to the disc. Possible deviations may disrupt the testing process, as the surface of the sample may be cut or counter sample might slide

on it. The problem can be bypassed. One of the methods consists in the initial commissioning of the station, except that the contact zone is covered with sandpaper. The disk rotates until the surface of the stem is leveled. In this way, possible non-parallelities are leveled, which ensures correct contact. This operation was performed for the purposes of this work.

The first parameter (coefficient of friction) is measured directly during the experiment as a function of time or number of disc revolutions, whereas the second parameter (abrasive wear factor) is determined based on the change (loss) of sample mass. The necessary data are obtained by weighing the sample before and after the test, and then the wear rate was calculated from the Archard equation. The samples were weighed using a RADWAG WAS 160/C/2O device with a measurement accuracy of 0.1 mg. The sample should be thoroughly cleaned before weighing using products such as acetone or thinner. Otherwise, the result may be affected by an error [28-31]. The aforementioned weight was also used to calculate sample density.

Choosing correct input parameters for the experiment can be difficult [32, 33]. Sometimes it requires a lot of work, and the accuracy of the results depends on the correctness of their choice [34, 35]. In this work, the parameters of the experiment, i.e. speed, friction distance, touch diameter, and friction pair load, were selected after preliminary tests of two additional samples.

Based on previous experience and preliminary test results, it was assumed that the parameters will be constant for all samples and will be equal respectively: speed $v = 1$ m/s, path $S = 1000$ m, touch diameter $d = 18$ mm, and load $Q = 5$ kg. Tests were carried out at 35% air humidity and 21°C ambient temperature. These parameters were measured using an MT886 hygrometer and a K-type thermocouple connected to the Velleman DEM106 sensor. The counter-sample was a cylinder (diameter 6 mm) made of gray cast iron (EN-GJL-250). In addition, their calorimetry and the thermal conductivity were determined using calorimeter and the hot wire method. Owing to the lack of this type of equipment at our University, the service of determining these material features was commissioned to a specialized company.

The aforementioned data, as well as the CAD drawing of real braking system components and mathematical model of the braking process described in article [36] were used for simulation tests. Tests were performed to determine the temperature profiles of friction phenomenon. The purpose of simulation tests was to determine how the material from which the samples for laboratory tests were made will be suitable for the brake pad production. It was assumed that the brake disc was made of gray cast iron, whereas the brake pad was made of the material from which the samples were made. The tests were performed four times, i.e. for each of the sample groups. The initial speed was set at 90 km/h. It was also assumed that the coefficient of friction between the tire and the road surface is 1, which gives braking deceleration of 9.81 m/s^2 . The dynamic radius of the tire was set at 250 mm (Fig 4) and the ambient temperature at 25°C . Additionally, the invariance of the coefficient of friction, constant contact pressure, constant braking delay, and no influence of external factors were assumed. The simulation time was set at 10 s, which allows to observe both the heating process during braking, as well as after stopping situation - heat release.

3. RESULTS AND DISCUSSION

The results of the first stage tests are summarized in Table 2. They show very clearly the lubricating properties of copper. This is manifested by a decrease in the coefficient of friction as the Cu content increases. This lubricity also has an opposite effect on the abrasive wear rate. However, good heat conductivity causes noticeable changes in capacity and thermal conductivity (table 2). Increasing copper content also results in higher material density. This is owing to the fact that copper is heavy. Its density is around 8.96 g/cm^3 ; therefore, it is higher than the density of most friction material components.

It is clear that the increase in copper content leads to a decrease in the degree of heating of the brake pad. The reason for this is the increased thermal conductivity of the material, which results in faster energy dissipation to the surroundings. This is a very desirable phenomenon, because the composite nature of the pad structure, in which the resin is used as the matrix, has limited resistance to

high temperatures. With intense heating, the phenomenon of fading may occur, which is a serious threat, as it may cause loss of braking ability. It can also be seen that when the pads' temperature drops, the disc temperature increases. The likely cause is increased heat conduction from the pad to the disc.

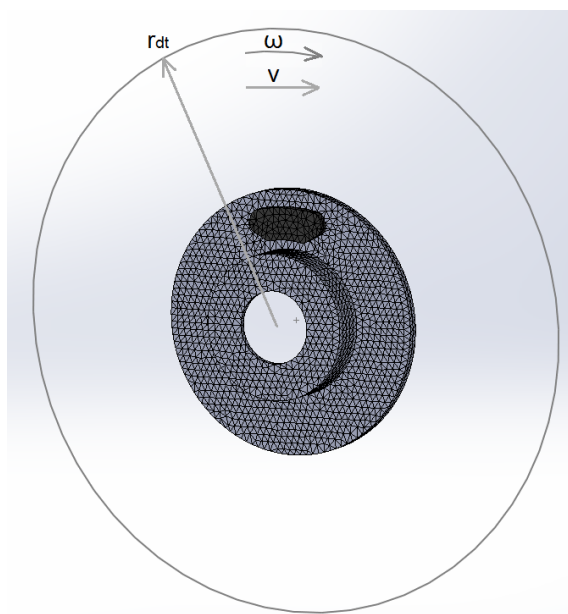


Fig. 4. Simulation scheme: v – linear vehicle speed (initially 90km/h), ω – angular speed of the wheel corresponding to the linear speed of the vehicle, r_{dt} – dynamic radius of tire

Table 2

Properties of prepared samples

Parameter	1st group of samples	2nd group of samples	3rd group of samples	4th group of samples
Heat capacity, J/(Kg °C)	728	703	670	650
COF	0.27	0.25	0.22	0.20
Heat conductivity, W/(m °C)	21	24	26	29
Density, $\times 10^3$ kg/m ³	2.85	2.9	2.95	3.01
Coefficient of abrasive wear rate $K_C, 10^{-13} \text{m}^3 \text{N}^{-1} \text{m}^{-1}$	168.13	153.48	109.74	98.85

During the second stage of the research - computer simulation - it was noticed how the changes in samples' chemical composition affects heating process of the friction material (Fig. 5 and 6). This type of testing is also widely used in transport, and not just for testing braking systems [37-39]. According to the authors of such models, after positive verification of the developed model, bench tests could be completely skipped, which significantly reduces the time of testing and their cost decrease to almost zero. In addition, it opens the possibility of testing quantities that are difficult or impossible to measure on a real stand, such as stress distribution on the contact surface of the friction kinematic pair [40-43].

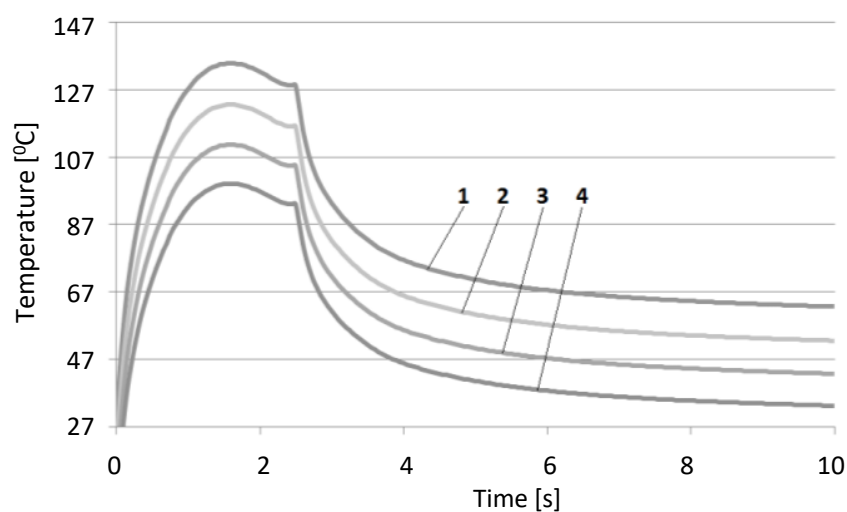


Fig. 5. Temperature profiles of brake pads made of material: 1 – 1st group of samples, 2 – 2nd group of samples, 3 – 3rd group of samples, 4 – 4th group of samples

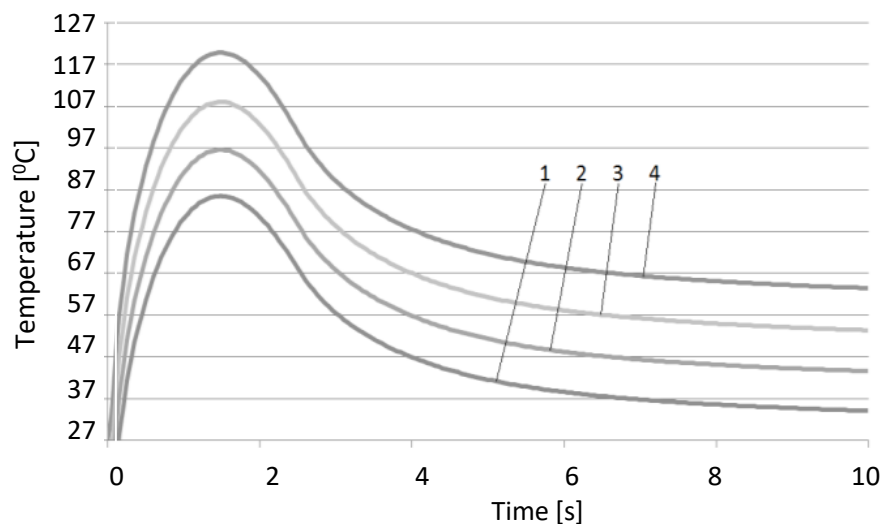


Fig. 6. Temperature profiles of brake discs during friction with pads made of material: 1 – 1st group of samples, 2 – 2nd group of samples, 3 – 3rd group of samples, 4 – 4th group of samples

4. CONCLUSION

Many vehicles of modern transport are equipped with copper-containing brake pads. High copper-content brake pads might reduce transport vehicles' exploitation costs because they are characterized by greater durability and better heat dissipation, which may be important during intensive braking [44]. Unfortunately, copper is harmful to health. Some countries have introduced regulations limiting the permissible fraction of copper in brake pads [14-19]. In the work, the four groups of samples made of different materials are presented. The materials of samples, as potential materials on the brake pad, are a mixture of graphite, powder glass, SiC, and copper.

The study allowed to make the following statements:

- Samples with low Cu content (5%) had the highest heat capacity (728 J/(kg°C)) and the highest friction coefficient (0.27); among all samples, they were also the lightest.

Unfortunately, owing to their characteristics, they were the fastest to wear and were the most heated during friction against gray cast iron.

- Samples with a high Cu content (20%), in turn, had a significantly lower heat capacity (650 J/(kg°C)) and (due to copper lubricity) a lower coefficient of friction (0.2); however, the lubricity significantly improved the material lifetime by reducing the value of the abrasive wear factor by approximately 40%.

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