JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
61, 4, pp. 807-818, Warsaw 2023
https://doi.org/10.15632/jtam-pl/172571

INFLUENCE OF THE SHAPE OF THE COPPER COMPONENT ON MECHANICAL PROPERTIES OF THE FRICTION MATERIAL USED IN DISC BRAKES

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Brakes are an important safety feature of vehicles. The materials of which the friction elements are made pose some risk to the environment. This can be a case during manufacture, operation and disposal. Any step to improve the ecology deserves thorough examination and possible introduction into production. For this reason, it has been decided to investigate whether it is possible to replace aramid with another material that is already present in its composition. The choice fell on copper, which was used in prepared samples in the form of both powder and fibers.

Keywords: friction materials, composite, mechanical strength, material properties

1. Introduction

Automobiles are extremely popular these days. Most households own one or more vehicles. It is estimated that the number of vehicles on our planet will increase to over 2 trillion by 2030. In addition, today's cars are characterized by much better performance. The combination of the above two factors can lead to dangerous situations on the road. Therefore, it is extremely important that vehicles are equipped with effective braking systems. The health or even lives of many road users may very often depend on their correct operation. The high level of today's scientific workshop provides the opportunity to develop solutions that can meet the restrictive requirements.

The most popular and widely used solution since the first horse-drawn carriages has been friction brakes (Eriksson, 2000). Then, as now, these brakes are a kind of converter of kinetic energy of motion into thermal energy (Kukutschová *et al.*, 2010). Such a solution, despite obvious advantages, unfortunately has its disadvantages. One of the biggest is the amount of heat generated during emergency braking, especially in vehicles with high weight (Kuciej *et al.*, 2020). For this reason, friction materials must have suitable properties that allow them to operate at such high temperatures, but also to dissipate the heat quickly enough to prevent overheating of the brake fluid, for example (Ertan and Yavuz, 2010). In addition, the friction materials used in vehicle brakes should be weather-resistant and pose as little risk to the environment as possible during manufacturing, operation, and recycling (Singaravelu *et al.*, 2019).

The friction layer of the brake pad is usually a composite material with different compositions depending on the manufacturer. There are several thousands materials as the basis for the components used, of which 10-20 are selected for a single product (Nagesh *et al.*, 2014). Like any composite, the pad must contain a reinforcement. Currently, this role is most often played by aramid, and sometimes by carbon or glass fibers. Unfortunately, as described in a previous work (Borawski, 2023), their production is associated with particular hazards for humans and the environment.

One of the most important pad materials is copper. It is a multifunctional and almost indispensable component of friction materials (Österle *et al.*, 2010). It does not only ensure structural integrity, but also significantly improves dissipation of frictional heat. Thanks to these properties, copper significantly reduces the risk of fading at high temperatures (Kumar and Bijwe, 2011). A major problem is the fact that copper, so necessary in friction materials, becomes one of the components of wear products released into the environment as a result of friction and rubbing. Unfortunately, as numerous studies have shown, it is a serious pathogen, especially for aquatic organisms, but also for humans, where it can cause severe multi-organ diseases (Azizishirazi *et al.*, 2013). For this reason, regulations have been introduced to limit the percentage content of this element in friction materials from 2025 (Hjortenkrans *et al.*, 2007). Therefore, numerous researchers have attempted to replace copper with organic fibers (Matejka *et al.*, 2013; Yun *et al.*, 2010), solid lubricants (Lee *et al.*, 2010), and various types of metals (Martínez *et al.*, 2014). However, the test results showed that none of the proposed materials was a fully satisfactory alternative to copper.

Considering the above fact, which is almost related to the necessity of using copper in brake pads, it was decided to test if copper could take over the role of aramid, i.e., serve as reinforcement in addition to its basic function. For this purpose, geometry of copper particles must be changed from spherical to fibrous. From a literature survey, the shape and size of the particles can have the following effects in the course of the friction process (Sellami *et al.*, 2020; Wojciechowski *et al.*, 2013; Kumar and Bijwe, 2011):

- the finer the copper particles, the better the lubrication properties and thus the lower coefficient of friction and greater resistance to abrasive wear;
- an irregular shape or sharp edges increase the value of the coefficient of friction;
- a higher copper concentration improves the lubricity and thermal conductivity of the final product.

In the previous works, it was shown that the shape of the copper could indeed affect the COF. Using fibers instead of round particles and removing aramid increased the coefficient of friction by about 13% (Borawski, 2023). The purpose of this work is to examine how the above change in the reinforcement method affects mechanical properties of the composite friction material.

It is considered that the most important mechanical properties of friction materials are hardness, density, compressive and shear strength, water and oil absorption, friction and wear resistance (Akíncíoğlu *et al.*, 2021). Literature review has shown that researchers more often focus on tribological than mechanical properties, which are equally important from an operational point of view. Wannik *et al.* (2012) studied samples produced with an addition of boron. The research results, such as hardness, porosity, and specific gravity, were compared to results for a commercial material. The bootstrap method was used to analyze the results. Bahari *et al.* (2012) investigated the hardness and wear resistance of friction materials with the addition of rice husk dust (RHD) at a concentration of 10% and 30%. The obtained results showed that RHD, especially at a concentration of 30%, had a positive effect on the hardness of the proposed prototype material. Comprehensive material studies were conducted by Parandaman *et al.* (2015). They focused on tensile, bending strength and additionally friction and wear tests. In their study, they prepared four groups of samples with different coconut fiber contents: 0%-15% by volume (5% increments). They also used a variable compression pressure (10-60 tons). It was found that the coconut fiber content of 5% and 10% gave the best flexural and compressive strength. A classical strength measuring machine was used for the tests. Gai *et al.* (2022) addressed a similar issue. The subject of their study was also four groups of samples, but they were cut from commercially available brake pads. The tests included determination of bending resistance, hardness, coefficient of friction and abrasion resistance. X-ray and scanning microscopy tests were also conducted. The researchers found that the composition of the material had a significant impact on the results of the tests performed. Accordingly, a higher carbon content had a positive effect on the mechanical strength of the friction material. They also found a coupling between hardness and wear rate. Mutlu *et al.* (2015) studied mechanical properties of the material samples he produced. Candlenut and coconut shells, which are rare in this role, were present in the composition. Their total content varied between 40% and 60%. The rest consisted of iron powder, carbon, resin and pineapple leaf fibers. The components were crushed with a mill and then pressurized in a hydraulic press. The semi-finished products were subjected to a pressure of 15 kPa and then heated at 100°C. Water absorption, hardness and tribological properties were tested on the finished samples. A chemical composition analysis was also performed using the EDS method. Again, a correlation between hardness and wear resistance was confirmed. The high content of plant-derived additives proposed by the researchers also improved resistance to water absorption. The mechanical properties of friction materials made of basalt were studied by Gai *et al.* (2022). It served as a filler. The other constituents were selected from the conventional range, i.e. resin as the matrix, glass fiber as the reinforcement, and bronze and cast iron as friction modifiers. The authors determined mechanical properties such as compressive strength, hardness, tensile strength and water absorption, among others. They found that the addition of basalt had positive effects, including an increase in the compressive strength or coefficient of friction compared to conventional materials. The tensile strength and thermal conductivity were even better than those of ceramic-based friction materials.

Based on this analysis, it was decided to conduct compression, bending, tensile strength tests and to measure the hardness and water absorption of water, brake fluid and oil. In authors opinion, these are the most important mechanical properties of composite friction materials, the values of which should be at a certain level.

2. Materials and methods

Each of the above studies required a different test, often performed at a different stand. Most of the tests were destructive, so individual samples were required. These were prepared according to the proportions given in Table 1. Component mixtures were measured using a Steinberg SBS--LW-300A balance. The materials were then mixed in a custom-built device using an additive technology (Fig. 1). The device was thoroughly cleaned and dried after each use. The final mixtures were poured in a mold and then placed in a hydraulic press and loaded with a force of $100 \cdot 10^3$ N for about 12 hours. After the load was removed, the samples were annealed at 60°C for 48 h. After this time, the molds were removed and the surfaces of the samples were ground to give them the desired shape, dimension and surface roughness.

Table 1. Composition of the prepared samples

Component	Contents [%]			
	S1	S2	S3	S4
CuZn20	12	12	12	12
Cu	25	25	25	25
S355 Steel	7	7	7	7
Aramid	12	8	4	0
Resin	17	17	17	17
Graphite	5	5	5	5
Fly ash	18	22	26	30
EN-GJS-400-12	4	4	4	4

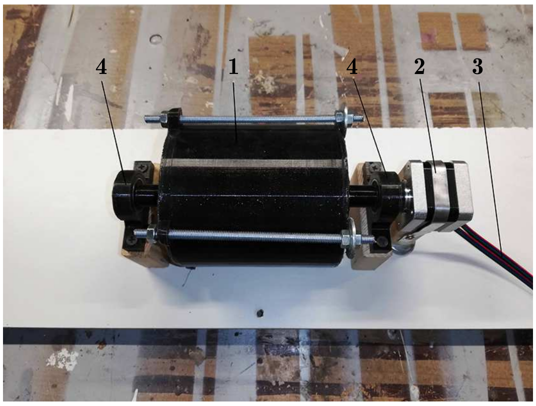

Fig. 1. Mixing of sample components: 1 – mixing unit, 2 – stepper motor, 3 – driver connection, 4 – bearing

2.1. Static compression test

The latest standard ISO 6310 provides for different test variants. They can be performed at both low and high temperatures. The test methods have also been divided into pneumatic (method A) and hydraulic (method B), depending on the type of a braking system. A maximum compression speed of 15 mm/min is also specified. The limit pressure is 10 MPa or 16 MPa – depending on the intended use of the material. This compressive strength test was performed using the Instron 8502 device (Fig. 2), which meets the requirements of the Standard. To maximize accuracy, the input parameters of the test were set as follows: feed rate 0.1 mm/s, measurement frequency 100 Hz. The samples prepared for this test were cylindrical, had a diameter of 20 mm and a height of 25 mm (Fig. 3).

Fig. 2. Compressive strength test

2.2. Static bend test

The brake pads are subjected to a small amount of bending under real conditions. It results only from the fact that the pad working on the inner side of the brake disk is pressed only in the central part, and the movement of the outer pad causes pressure to the caliper on the opposite

Fig. 3. Samples tested in compression test

edges. The fact that the friction material is mounted on a steel support plate further reduces the effects of bending versus compression and stretching on potential damage. Nevertheless, bending does occur, therefore it was considered reasonable to perform a static bending test to obtain a more complete picture of the mechanical properties of the proposed material.

The Instron 8502 apparatus was used for the tests. The technical standard BN 0601-12-1 suggests that the bending tests should be performed with a three-point support – two lower fixed supports, and the upper one movable. The maximum feed rate of the breaking mandrel was set at 5 mm/min. A prerequisite for correctness of the test is that the cracks occur at a distance of no more than 10 mm from the load application. Therefore, to maximize quality of the results, the speed was set to 0.05 mm/s (3 mm/min). The recording frequency was set to 100 Hz as before. Rectangular samples with dimensions of 12 mm×12 mm×90 mm were used in the study (Fig. 4). According to the Standard, the distance between the supports was 75 mm and the load was applied centrally (Fig. 5).

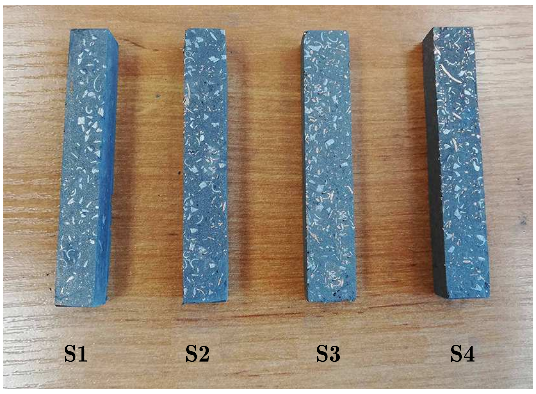

Fig. 4. Samples made for bending tests

Fig. 5. Bending resistance test

2.3. Static tensile test

The basis for this type of test is the standard ISO 6892-1:2019. The test described therein is simple and consists of uniaxial stretching of a material sample. The prerequisite for correct performance is the use of self-centering holders that ensure the required stress state. The above Standard recommends that the stress increase rate in the sample be between 2 MPa/s and 20 MPa/s.

In this case, Instron 8502 was also used with special holders that allow the centering of the sample (Fig. 6). The input parameters for the test were assumed to be a feed rate of 0.05 mm/s and a maximum displacement of 50 mm. This ensured the correct stress increase rate.

The samples used in the test were the same as in the bending test – rectangular with dimensions 12 mm×12 mm×90 mm.

Fig. 6. Tensile strength test

2.4. Hardness measurement

The hardness of the prepared samples was measured ten times at randomly selected points for each sample. This was necessary because the composite material was generally not homogeneous. The tests were carried out with the PRL 610 hardness tester (Fig. 7).

The final test result was the arithmetic mean. The standard deviation for each measurement was calculated according to the following formula

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{2.1}$$

where: s – standard deviation, n – number of measurements, x_i – result of the i-th measurement, $\overline{x}$ – arithmetic mean of the results for a given sample.

Fig. 7. Hardness tester PRL 610

2.5. Measurement of water, brake fluid and oil absorption

This parameter is extremely important, as the properties of the friction material can change when saturated with a liquid. The most influential substances here are oils (which can reduce the coefficient of friction) and brake fluids (whose corrosive properties can reduce structural integration of the composite material). Absorption is closely related to porosity. Some manufacturers deliberately design the friction material to be highly absorbent, which they believe improves heat dissipation from the friction junction (Gai *et al.*, 2022). According to the applicable Standard, i.e. ISO-6314, cylindrical samples (diameter 1″, height 20 mm) immersed in liquids and left for 7 days were tested. These fluids were water, common 5W30 viscosity grade motor oil and DOT4 brake fluid. Each sample was thoroughly cleaned and weighed prior to testing using a Steinberg SBS-LW-300A precision balance and then measured with a micrometer. After testing, the surface of the samples was dried with paper towels, then weighed and measured again. Based on this data, the water absorption could be determined.

3. Results and discussion

The results of the strength tests are presented in Fig. 8-10. The static compression test showed that all samples submitted for testing had similar strength. Sample S3 had a slight advantage over the others, withstanding stresses of nearly 79.6 MPa.

The results obtained in the tensile and bending tests turned out to be extremely interesting and surprising. When samples with a high aramid content (S1 and S2) were bent, clear fiber breaks could be seen. These materials resemble brittle materials in their properties. Changing copper geometry from powder (S1) to fiber (S2) increased the allowable stresses by almost 50%. The most favorable sample was S3, which exhibited properties similar to a plastic due to the small amount of aramid and long copper fibers. This sample showed a stress limit of just over 80.7 MPa. The worst performing sample was the one in which the aramid was completely replaced by copper fibers – a much more ductile metal. As a result, S4 composite lost a significant amount of its strength, for which the reinforcement was responsible. The maximum stress is only 26 MPa, which is just under 30% of the value achieved by S3 sample.

During the tensile test, S3 sample also proved to be the strongest, reaching the allowable stress of 9.2 MPa. Samples with a higher content of aramid and copper in the form of shorter fibers (S2) and powder (S1) turned out to be weaker, but reaching the limit stresses took more time. All samples containing aramid (S1-S3) showed clear characteristics of brittle materials. The last sample (S4), where aramid was completely replaced by copper fibers, behaved like a typical plastic material. The stress buildup was much slower, and there was no clear fracture boundary. The cause for such behavior should be sought in the properties of copper.

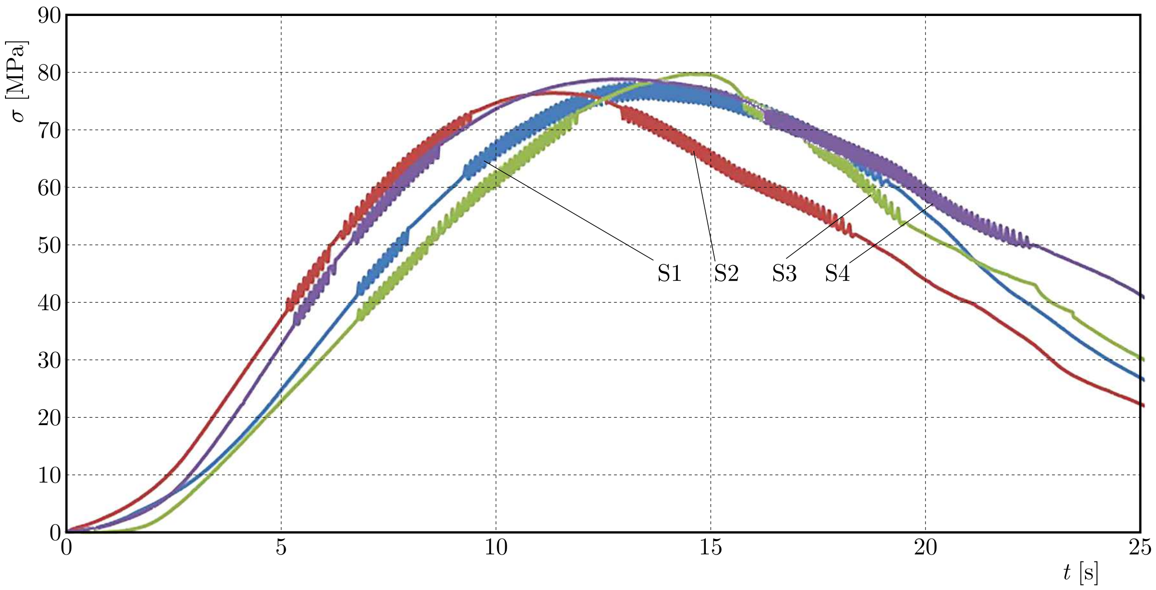

Fig. 8. Static compression test

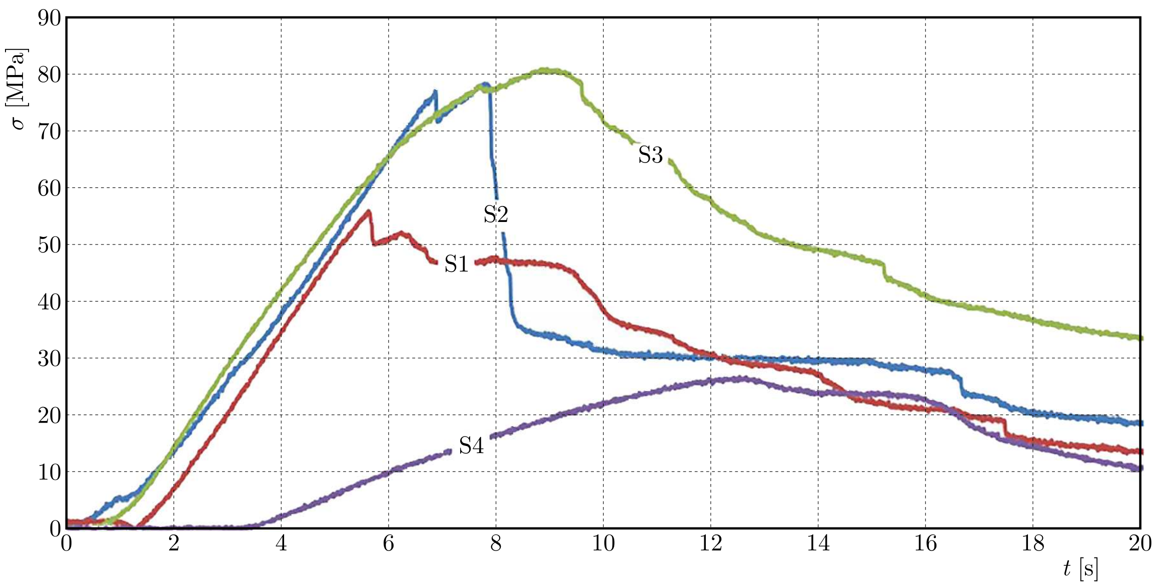

Fig. 9. Static bend test

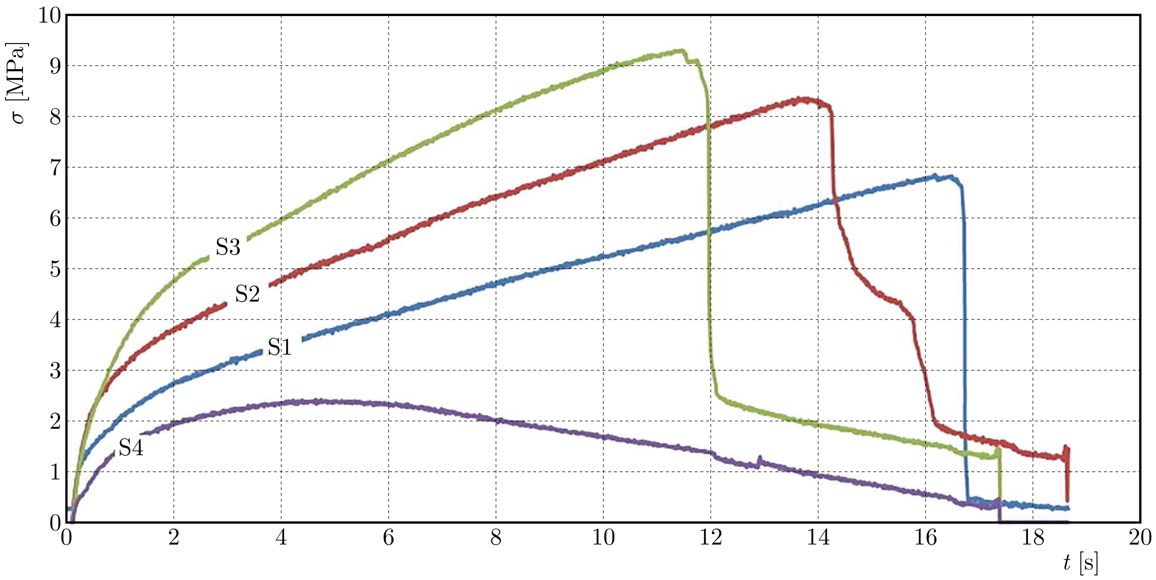

Fig. 10. Static tensile test

The results of the hardness test are shown in Fig. 11. This parameter is closely related to mechanical strength. It determines the resistance to plastic deformation, penetration, scratching or frictional wear. The measurements showed that the values for samples S1-S3 were similar. Taking into account the standard deviation, whose high value results from the fact that the object of study is a composite material, it can be assumed that the samples of these three groups have the same hardness. The results for sample S4, taking into account the standard deviation, are within the above range, but the average value here is the lowest. A clear reflection is visible in the strength tests described above.

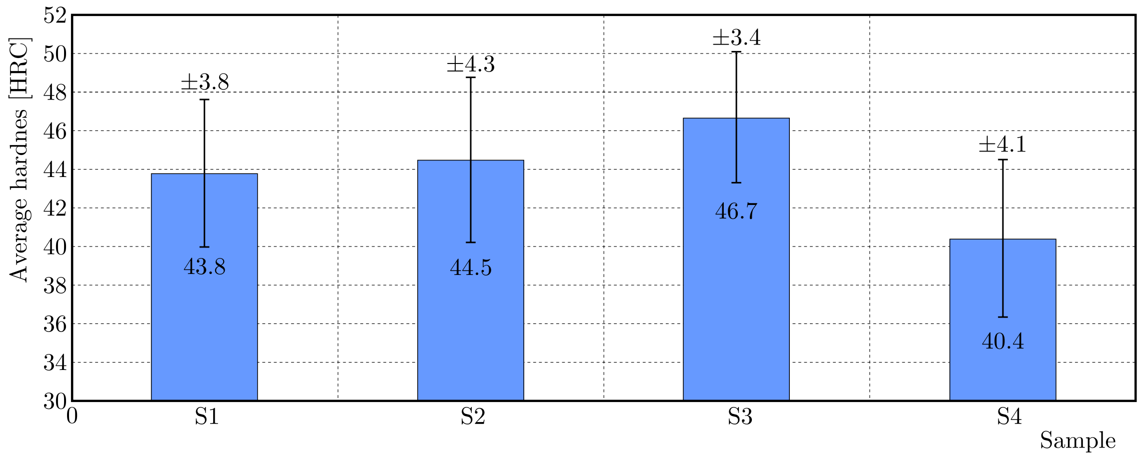

Fig. 11. Hardness test results

The results of the fluid absorption tests are shown in Table 2. After the measurements were completed, the liquid on the surface of each sample was wiped off before it was calcified. The final absorbance value was calculated using the following equation

$$A = \frac{M_f - M_i}{M_i} \cdot 100\% \tag{3.1}$$

where: A – absorption, M_f – mass of the sample after immersion in liquid, M_i – initial mass.

The above values show that all samples are characterized by similar, low absorption. Slight variations are due to random factors in the production process.

Table 2. Results of liquid absorption tests

Substance	Sample	M_i [g]	M_f [g]	Mass gain [g]	A [%]
Water	S1	30.269	30.404	0.135	0.445
	S2	30.771	30.960	0.189	0.615
	S3	31.604	31.719	0.115	0.364
	S4	31.743	31.947	0.204	0.644
5w30 oil	S1	30.762	30.873	0.111	0.362
	S2	31.637	31.853	0.216	0.683
	S3	31.204	31.356	0.152	0.486
	S4	31.097	31.247	0.150	0.481
Water	S1	30.576	30.777	0.201	0.659
	S2	31.215	31.334	0.119	0.380
	S3	31.261	31.386	0.125	0.399
	S4	31.369	31.539	0.170	0.542

4. Summary

This paper presents the results of tests of the mechanical properties of composite materials. These prototype materials were developed with the intention of being used in braking systems. The prepared samples differed in the type of reinforcement. It has been found that:

- the best strength properties and the highest hardness are obtained when a significant part of the aramid reinforcement is replaced by a copper one with moderate fibre length (sample group S3),
- the type of reinforcement used has no effect on the absorption of water, oil and brake fluids,
- the complete absence of a conventional reinforcement with the properties of a brittle material leads to a significant reduction in the mechanical properties of the composite friction material, making it more plastic.

Summing up, it is possible to reduce the aramid content and thus the environmental impact generated during the manufacturing process, while improving the mechanical properties of the composite. This can be achieved by changing the geometry of copper particles from powder to fibre.

Acknowledgments

The research was carried out as a part of work No. WZ/WM-IIM/5/2023 at the Białystok University of Technology and financed from the research subsidy provided by the Ministry of Science and Higher Education.

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Manuscript received June 30, 2023; accepted for print August 16, 2023