# SOME TRIBOLOGICAL CHARACTERISTICS OF DISC BRAKE PADS

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## Summary

The article presents results of experiments carried out to investigate the impact of modelled conditions of the vehicle operation and its environment on the coefficient of friction in the disc brake friction pair. The influence of these factors on the scatter of values of the coefficient of friction was analysed. The tests were carried out in laboratory conditions on a test stand provided with appropriate instruments and equipment. The friction pair was modelled by a set-up of materials as used in passenger car brakes, consisting of a cast-iron brake disc and composite brake pads. Time histories of the coefficient of friction in the friction pair were tested at various operating conditions (rotational speed of the brake disc, number of braking cycles) and environmental factors (presence of water or brake fluid in the friction area). Changes in the surface roughness of the cast-iron brake disc resulting from the application of various brake pad materials and from different operating conditions and parameters set on the test stand were examined as well. The histories and values of the parameters measured as recorded during the tests were used as input material for analyses. The results of the research work and the conclusions drawn that are applicable to the analysis of criteria of the acceptable differences between the braking forces measured on diagnostic roller test stands have been presented here in a synthetic form.

**Keywords:** disc brakes, friction linings, coefficient of friction, humidity of linings.

## 1. Introduction

The braking system is one of the critical systems of a vehicle, extremely important for active safety. Its effective, efficient, and reliable functioning is a prerequisite condition of safe driving. The length of the braking distance is determined by *inter alia* the braking torque applied to vehicle wheels by the wheel brake mechanism. With certain simplification, we may state that the braking torque applied to one wheel is a product of the friction force developed between the brake pad and disc or between the brake lining and drum and the friction force arm equal to the inner radius of the brake drum or the arithmetic mean

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between the maximum and minimum radii of the area of contact between the brake pad and the brake disc for drum and disc brakes, respectively. In brake mechanisms, the braking torque is directly influenced by the force with which the brake pad or lining is pressed against the brake disc or drum and by the value of the coefficient of friction between the elements rubbing against each other.

The functions to be fulfilled by the braking system and the conditions in which the braking system is to operate dictate certain requirements that must be met by the materials used for the friction pairs taken as a whole, i.e. the brake pad and brake disc or the brake lining and brake drum. The requirements arise not only from the necessity that the brake mechanism must fulfil its basic function, i.e. it must control the vehicle speed, but also from the fact that the braking system must not adversely affect the ride comfort. The mass production of motor vehicles and the price competition enforce reductions in the vehicle production and operation costs. The demands that the harmful environmental impact of the products of wear of the friction pair materials should be reduced to minimum constitute another group of expectations formulated in relation to braking system components.

In spite of ongoing introduction of new groups of materials to the construction of braking friction pairs, grey cast iron and asbestos-free polymer-organic friction elements still remain the basic materials used for this purpose. According to literature, if the brake assembly components are appropriately designed in respect of reducing their thermal loading then the brakes with cast-iron brake discs and polymer-organic brake pads constitute a very effective solution from the point of view of optimising the braking performance and rationalising the vehicle manufacturing and operation costs. Such brakes are still a subject matter of development work [1, 2, 4, 5].

## 2. Purpose of object of the research work

The work was undertaken to investigate the impact of various vehicle operation conditions on changes in the coefficient of friction in the disc brake friction pair. The tests were carried out in laboratory conditions on a test stand provided with appropriate instruments and equipment. The object tested was a friction pair defined as a wheel brake mechanism of a passenger car, consisting of a cast-iron disc brake and composite brake pads.

## 3. Properties of the materials making the brake disc and brake pad friction pair

At present, grey cast iron is most commonly used as a material for the production of brake discs of motor vehicles. In spite of numerous drawbacks of this material such as high specific gravity or poor corrosion resistance, the list of its good points predominates. The grey cast iron is characterised by favourable tribological properties and low price. In the case of parts made from this material, the production process methods have already been well mastered and no problems are encountered, either, with the disposal of worn-out products. In most cases, brake discs are made from grey cast iron, where graphite precipitates have the form of flakes, although spheroidal graphite iron is also used. The adding of appropriate alloying agents makes it possible to improve the corrosion resistance, but such a solution is not too frequently applied because of the resulting increase in production costs.

Various technical innovations such as material changes or lightening holes introduced in the brake disc design to reduce the total vehicle mass produce some favourable effect but the necessity to maintain adequate mechanical strength of this vehicle component makes this benefit not as conspicuous as it is when other materials, e.g. composites based on light metal alloys, are used [1, 3, 5, 7].

Cast-iron brake discs are shaped in the production process by the machining of castings. The cast brake disc blanks should have no casting defects because the cyclic nature of disc loads would quickly result in damage to such parts during operation. The discs are machined by turning and then their friction surfaces are ground for the required surface roughness parameters to be achieved. The relieving of internal process stresses in the discs makes it possible to reduce the risk of disc deformations during use; therefore, appropriate thermal treatment or seasoning of blanks is applied before the discs are put into service.

It should be emphasised here that one of the most important features of cast-iron brake discs from the disc operation point of view is the condition of the working (friction) surface of the disc because this surface is not homogenous, being divided into areas of pearlitic and ferritic structure and other areas where graphite precipitates predominate. Thanks to such an overall structure of the friction surface, high-frequency vibrations are damped.

The features considered most important may be indicated not only for brake discs but also for friction materials. In the latter case, vibration-damping capacity may be mentioned as an example; as a rule, the friction materials are heat insulators and their thermal conduction characteristics differ from those of cast iron; when rubbed, such materials emit wear process products to the environment.

The friction material components may be classified in four basic groups. The structural components cause the material to have appropriate strength characteristics. In most cases, they have the form of fibres and their surface having been chemically activated should ensure good adhesion to the binder. Thanks to higher thermal conductivity, metallic fibres perform an additional function, i.e. they carry away heat from the friction material. Appropriate fibre orientation and structure makes it possible to obtain desired heat conduction characteristics. Binding agents bind together individual components of the friction material. As the binding agents, phenol resins or synthetic rubber are usually used. The other two groups may be defined as filling agents (fillers) and friction modifiers. The latter group includes the components the role of which is to keep the friction coefficient values stable during the operation of brakes over a wide range of the brake operation conditions. They include metal sulphides, graphite, coke, aluminium oxide, barite, chalk, or zircon sand [1, 2, 4, 6].

At present, the stuff collectively defined as "asbestos-free organic friction materials" finds the widest application in motor vehicle brakes, with fibres of various kinds, such as metallic, glass, aramid, and mineral fibres, being used as the basic structural component of such materials [8,9].

The mechanical strength of friction materials chiefly depends on the types of the structural components and binders used. The thermal resistance is determined by characteristics of the organic components, which are the first to undergo degradation under the impact of raised temperatures. A typical organic friction material consists of over twenty components.

A characteristic feature of such materials is low thermal conduction. For the operation of the friction pair, this has the meaning that most of the friction heat generated goes to the brake disc. To meet the increasingly stringent requirements concerning the thermal loads of brakes, materials with increased metallic contents have been introduced. Metallic components may fulfil structural functions, i.e. constitute the matrix of the brake pad, as well as play the role of filler. In the former application, they have the form of fibres, while metallic powders are used in the latter case. Metallic components have a decisive impact on thermal characteristics of the friction material. Higher concentration of metallic components results in better thermal conduction. A favourable effect of better thermal conduction is the fact that heat is faster carried away from the friction area. This, however, is connected with the necessity to insulate the brake pad from the hydraulic piston in the brake calliper in order to prevent the transfer of excessive heat amounts to brake fluid [5, 6, 7].

The brake pad production process includes thermal treatment by holding the pads at a raised temperature to improve performance characteristics of the pads that have to operate in high temperature conditions when the brakes must be repeatedly applied with high intensity. When the pads are held at a raised temperature, degassing takes place in the compacted mouldings of the friction material. This process prevents a loss of friction ability of the brake friction pair in result of the forming of a gaseous phase between the friction surfaces when the brakes are intensively used in extreme vehicle operation conditions.

## 4. Results of testing the coefficient of friction of the brake friction pair

The investigation of the impact of the actual condition of a disc brake friction pair on the coefficient of friction in this pair and the subsequent evaluation of variations in the values of this coefficient is of significant importance for the analysis of the braking process. The objective of this part of the research work was to determine the impact of the type of a brake pad in its nominal condition on the value and scatter of the coefficient of friction in the friction pair involved. Results of this work should be taken into account at defining the acceptable differences between the braking forces measured during diagnostic examination of vehicle brakes on roller test stands [9].

The following conditions were adopted for the tests carried out on the test stand:

- The rotational speed of the brake disc could vary within a range from 26.2 to 87.2 rad/s, which corresponded to the vehicle linear speed ranging from 30 to 100 km/h;
- The average length of the friction force arm was 0.092 m;
- The unit pressure between the working surfaces of the friction pair ranged from 320 to 530 N/cm$^2$, which corresponded to a fluid pressure in the braking system of the model passenger car ranging from 6 to 10 MPa, i.e. the brake fluid pressure occurring at hard braking;
- The friction pairs under tests were tribological systems consisting of brake pads and cast-iron brake discs; the friction material of the brake pads was made to four different process methods and the friction surfaces of the brake discs were ground to obtain a surface roughness of $R_a$ = 0.25 μm.

The friction coefficient values obtained in result of experiments carried out for friction pairs consisting of cast-iron brake discs with surface roughness as specified above and brake pads manufactured to different process methods (by different manufacturers) have been presented in Table 1.

**Table 1. Average values of the coefficient of friction in the friction pairs under tests**

| **Process method (manufacturer)** | **Average value of the coefficient of friction** $\mu_{av}$ | **Standard deviation** $S(\mu)$ | $S(\mu)/\mu_{av}$ **[%]** |
|---|---|---|---|
| I | 0.54 | 0.005 – 0.02 | 0.9 – 3.5 |
| II | 0.55 | 0.01 – 0.02 | 2.4 – 3.8 |
| III | 0.53 | 0.02 – 0.03 | 1.3 – 5.8 |
| IV | 0.39 | 0.005 – 0.01 | 1.3 – 2.6 |

Significant scatter in the friction coefficient values was observed, as the values ranged from 0.39 to 0.54 (see Table 1). Visual examination of the condition of the friction surfaces, confirmed by spectrographic examinations, revealed distinct differences to exist between the brake pads made by different manufacturers, regarding the granulation and distribution of individual material components, the degree of compacting and tightness of material structure, as well as the quantity and distribution of the filler and metal particles carrying away heat from the friction surface. The factors as indicated above have a significant impact on the coefficient of friction and the characteristics of interaction between elements of the brake friction pair.

The coefficient of friction measured for friction pairs with materials made by different manufacturers changed, i.e. rose by 5 to 40%, during a single braking process (Figs. 1 ÷ 4). Individual braking tests were carried out in conditions corresponding to those occurring at long-lasting normal braking on a road. The least changes in the friction coefficient values were recorded for the brake pads made by manufacturer IV.

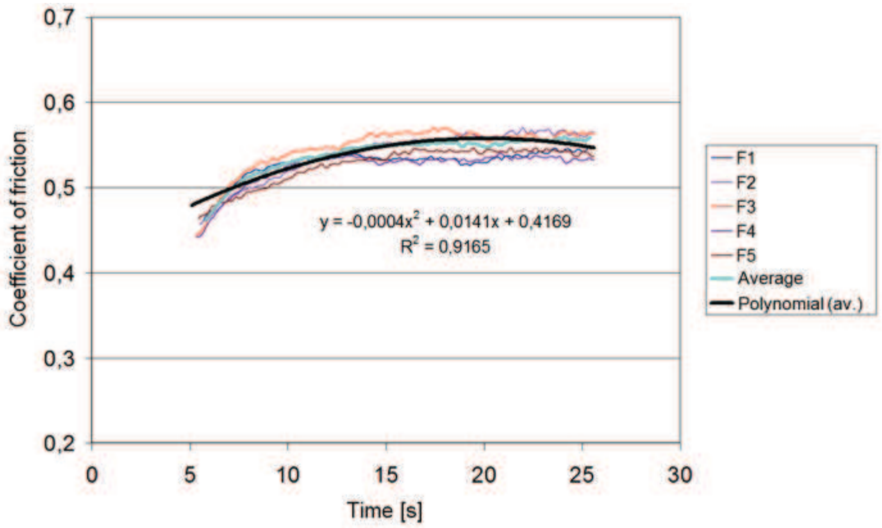


**Fig. 1. Changes in the coefficient of friction of brake pads during a single braking process. Manufacturer I; test conditions: $p$ = 530 N/cm$^2$, $n$ = 500 rpm = 52.3 rad/s**

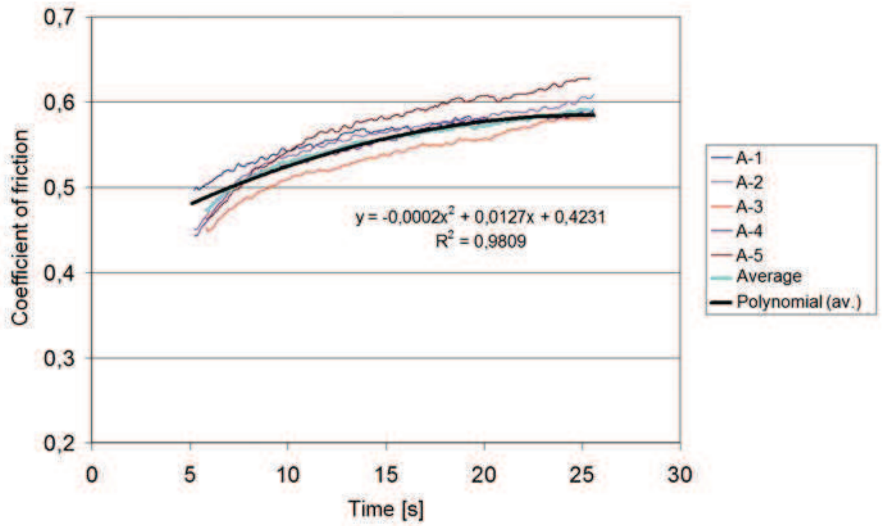


**Fig. 2. Changes in the coefficient of friction of brake pads during a single braking process. Manufacturer II; test conditions: $p$ = 530 N/cm$^2$, $n$ = 500 rpm = 52.3 rad/s**

The tests carried out showed the changes in the friction coefficient values to be caused by the friction heat generated during the braking. This finding was confirmed by measurements of temperature of the brake disc, because the temperature of the friction surface continuously rose during the 20 s time of duration of the braking process. The

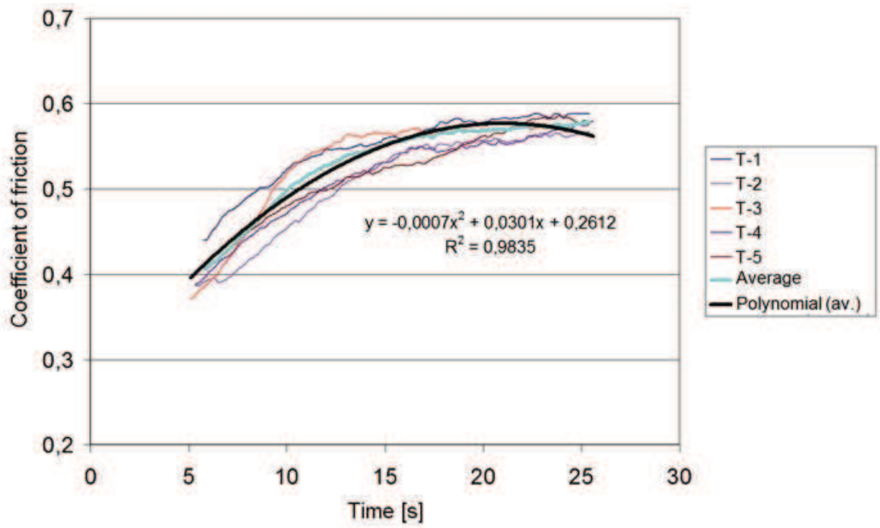


**Fig. 3. Changes in the coefficient of friction of brake pads during a single braking process. Manufacturer III; test conditions: $p$ = 530 N/cm$^2$, $n$ = 500 rpm = 52.3 rad/s**

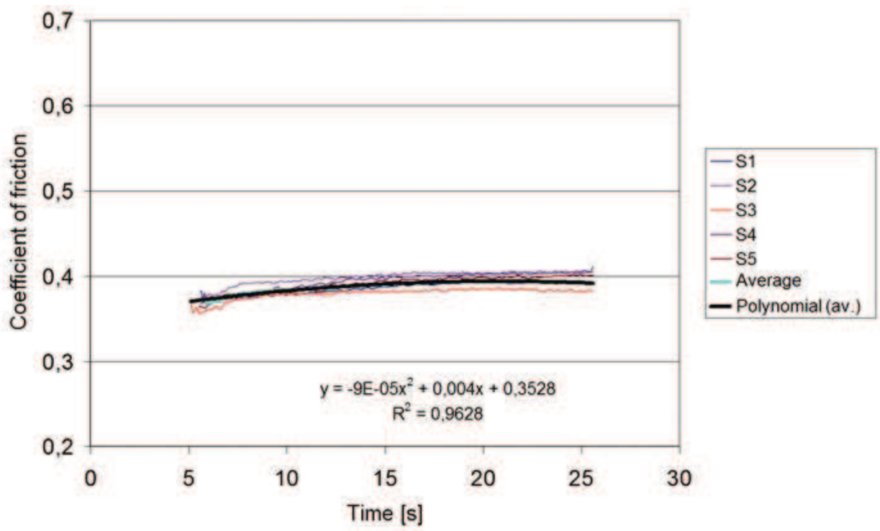


**Fig. 4. Changes in the coefficient of friction of brake pads during a single braking process. Manufacturer IV; test conditions: $p$ = 530 N/cm$^2$, $n$ = 500 rpm = 52.3 rad/s**

dependence of the coefficient of friction on temperature has been shown in Fig. 5. This dependence was determined for a relatively narrow range of changes in the brake disc temperature, corresponding to the changes that take place during vehicle braking in urban traffic conditions.

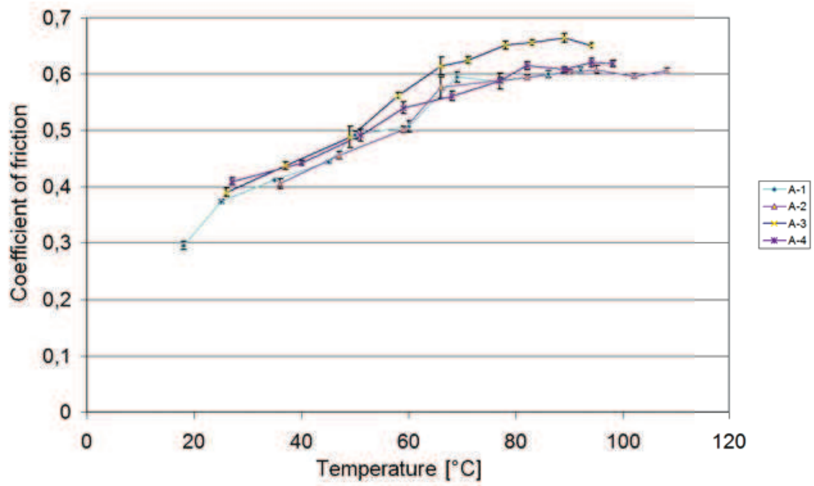


**Fig. 5. The impact of changes in the temperature of the friction pair on the coefficient of friction. Test conditions: $p$ = 425 N/cm$^2$, $n$ = 500 rpm**

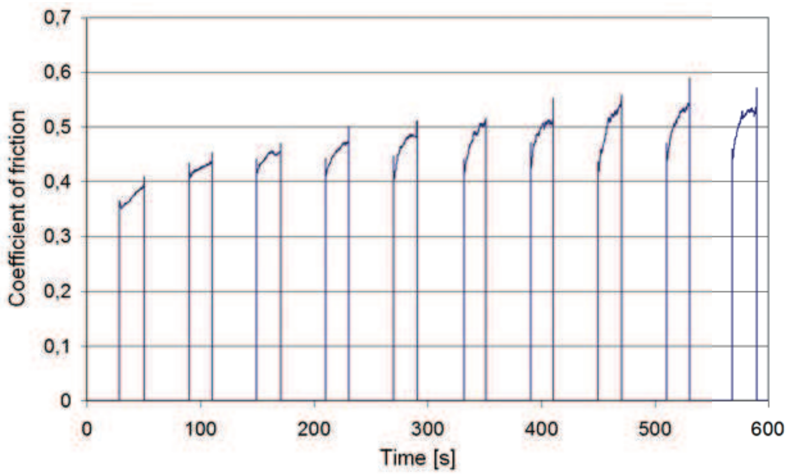


**Fig. 6. Changes in the coefficient of friction in the disc brake friction pair during the running-in period. Manufacturer I; test conditions: $p$ = 425 N/cm$^2$, $n$ = 500 rpm**

The period of running-in of new brake pads to the brake disc was also tested. During multiple repeated braking, the coefficient of friction considerably increased. At the beginning of the running-in period, the friction coefficient value made about 66% of that measured at the final stage of this process (Fig. 6). The increase took place during the first several dozen applications of brakes. During this process, the surface roughness of the brake disc considerably changed (Fig. 7). Originally, the surface roughness of the brand new cast-iron

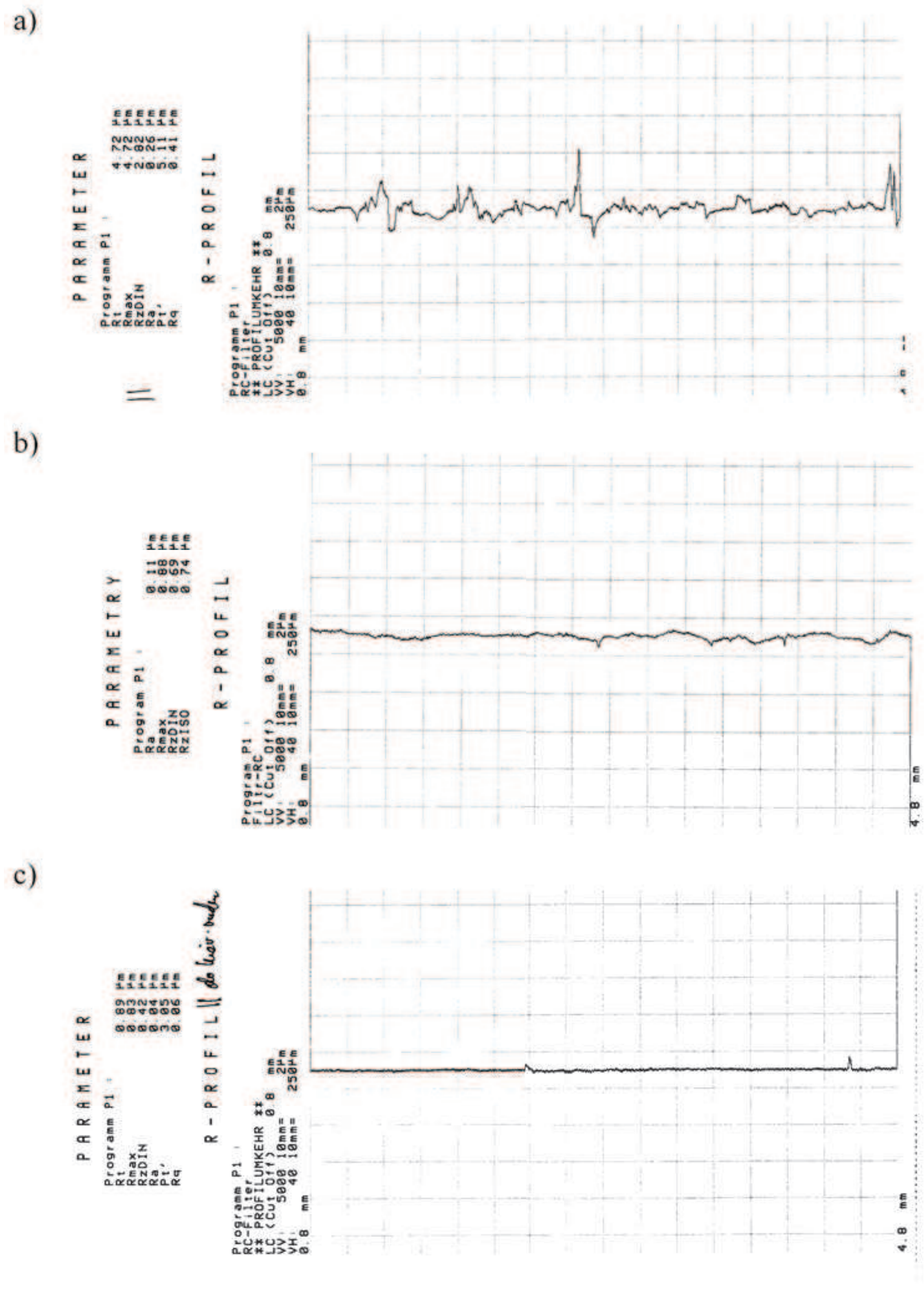

Fig. 7. Profilograms of the brake disc friction surface, taken along the direction of motion:
a) new disc (ground); b) disc after 10 braking cycles; c) disc after 200 braking cycles

disc was $R_a$ = 0.26 μm. After 10 braking cycles, the surface roughness parameter dropped to a value of $R_a$ = 0.11 μm and the friction coefficient value increased by about 30%. After 200 braking cycles, the disc surface roughness was $R_a$ = 0.04 μm.

## 5. Research on the impact of water on the coefficient of friction of brake pads

It is an inherent design feature of disc brake mechanisms that they are exposed to the impact of external factors. It is normal in the conditions of operation of braking systems that brake pads get damp, brake discs are temporarily or permanently wet, and all these parts become contaminated. This is due to the easy access of contaminants of any kind to the area of interaction between friction elements. One of the objectives of the research work carried out was to assess the impact of external (atmospheric) factors, e.g. water, and internal (vehicle-related) factors, e.g. brake fluid, on the functioning and performance of the disc brake friction pair.

The impact of dampness of the friction surfaces in the brake mechanism on braking performance was assessed on the grounds of rig test results, with analysing the history of the coefficient of friction in the friction pair exposed to water attack during the process of braking.

The tests were carried out for two values of the rotational speed, i.e. 530 rpm and 250 rpm, which corresponded to vehicle drive speeds of 64 km/h and 30 km/h, respectively, and

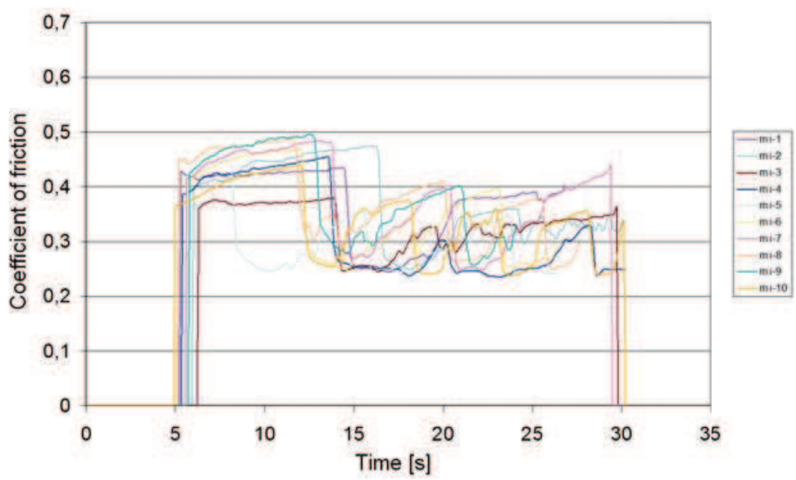


**Fig. 8. Time histories of the coefficient of friction, with the condition of the brake friction pair being changed from dry to wet, for 10 braking tests. Test conditions: $p$ = 425 N/cm², $n$ = 500 rpm**

for two brake disc wetting modes, i.e. temporary and continuous wetting. The test results have been presented in Figs. 8, 9, and 10.

When the braking test was started from a speed of 64 km/h with the brake disc being dry and then the disc was wetted during the test, the wetting resulted in a sudden drop in the coefficient of friction by about 40%. After about 1.5 to 3 s from the wetting, the coefficient of friction gradually increased to a level of about 80% of that recorded for the friction pair with dry brake disc. After the test, the temperature of the brake disc was about 40°C. The increase in the coefficient of friction resulted from the fact that water was automatically removed from the disc. At the tests carried out with a lower initial speed, corresponding to a vehicle speed of 30 km/h, the single wetting of the brake disc caused the coefficient of friction to drop by about 30% and this coefficient remained low for several seconds (Fig. 9), much longer than it was at the initial speed of 530 rpm (cf. Fig. 8). This may be probably explained by lower values of the centrifugal forces acting on water droplets and, in consequence, slower rate of the self-cleaning process.

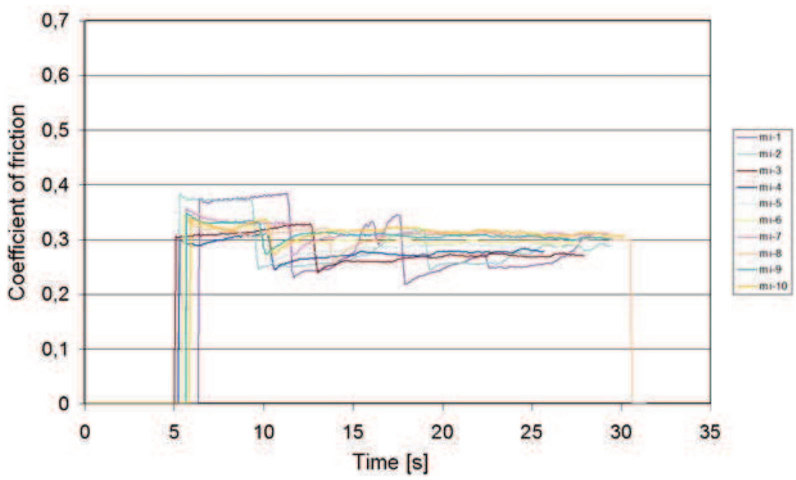


**Fig. 9. Time histories of the coefficient of friction, with the condition of the brake friction pair being changed from dry to wet, for 10 braking tests. Test conditions: $p$ = 425 N/cm$^2$, $n$ = 250 rpm**

At the braking test carried out with continuous wetting of the brake disc, the coefficient of friction permanently remained on a low level of below 0.3 (Fig. 10) as against the values of 0.4 to 0.45 recorded when the friction pair was dry. Such an effect occurs at vehicle speeds ranging from 30 to 40 km/h, i.e. in urban traffic conditions, when the automatic removal of water from the brake disc is rather poor.

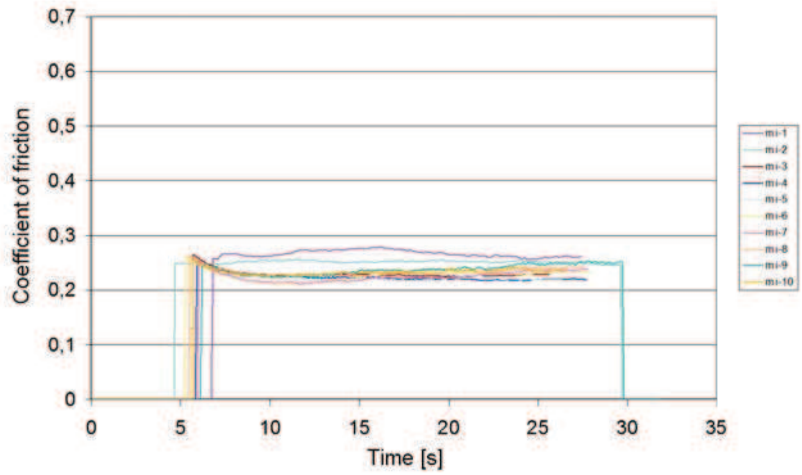


**Fig. 10. Time histories of the coefficient of friction, with the brake friction pair being continuously wetted, for 10 braking tests. Test conditions: $p$ = 425 N/cm$^2$, $n$ = 250 rpm**

## 6. Research on the impact of brake fluid on the coefficient of friction

Results of evaluation how the presence of brake fluid in the friction pair affects the braking performance have been presented in graphs in Fig. 11. They depict time histories of changes in the coefficient of friction during multiple braking. The first braking cycle was started with the brake disc and pad being dry and then the brake disc was moistened with brake fluid during the braking. The next braking cycles were carried out with the same brake disc, without cleaning it, and the moistening of the disc with brake fluid was repeated during the braking.

The time histories of the coefficient of friction determined for the friction pairs with brake pads made by various manufacturers did not considerably differ from each other. The appearance of even a small quantity of brake fluid on the friction surface of the brake disc resulted in a radical drop in the coefficient of friction in comparison with the value observed when the disc was dry. The first braking cycle presented in Fig. 11 depicts the interaction between the brake pad with the dry disc. The introduction of brake fluid into the contact area within the friction pair caused a very significant drop, by about 70%, in the coefficient of friction. At the next braking cycles, the friction coefficient value did not exceed a level of 0.1 and did not show any rising trend. This means that the brake fluid once absorbed by the contacting surfaces of the friction elements remains present there and significantly reduces the coefficient of friction. It was also observed that the next moistening of the rubbing surfaces with brake fluid caused the coefficient of friction to drop by another 50% (Fig. 11), but this was a short-lived effect followed by an increase in this coefficient. This tendency to rise, resembling a regeneration ability of the friction material, probably depends on the material structure. In the case of the brake pad specimens made by manufacturer I, the re-application of brake liquid caused a temporary drop in the coefficient of friction to a value of about 0.05 followed by a phase of slow-rate rising trend in this coefficient; for the pads made by manufacturer II, the regeneration effect, i.e. the recovery of the coefficient of friction to its value preceding the re-application of brake fluid, came within a much shorter time. In both cases, however, the coefficient of friction did not recover to its value as measured for the friction pair being dry (about 0.35 to 0.39) and remained on a level close to that recorded when the disc was moistened with brake fluid for the first time (about 0.1).

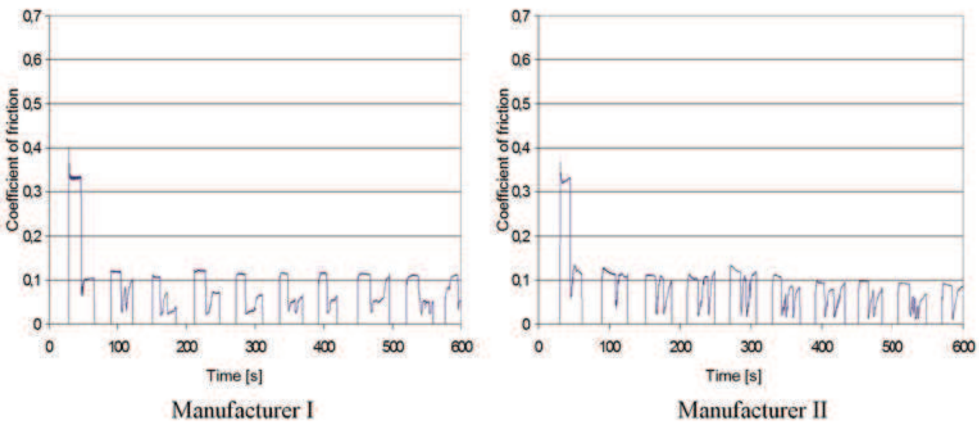


**Fig. 11. Changes in the coefficient of friction in the disc brake friction pair contaminated with brake fluid. The tests were carried out for two different brake pad materials Test conditions: $p$ = 425 N/cm$^2$, $n$ = 250 rpm**

## 7. Conclusions

1. The tribological experiments have revealed that differences of the order of 4% may occur in the coefficient of friction between friction pairs with brake pads made by the same manufacturer. The friction surface temperature has also been observed to have a significant impact on the friction coefficient value.

2. In consideration of the revealed differences in friction coefficient values and the accuracy of diagnostic roller test stands of the order of 5% of the measured braking force value, a statement should be made that for brand new braking system components

in full running order, the results of testing the braking forces on the right and left wheels on diagnostic test stands are likely to differ from each other by about 10%. Such a difference should not be considered a functional defect of the braking system because it may result from normal scatter in the characteristics of friction materials and from the properties of measuring stands.

3. If the brake of one of vehicle wheels is suddenly wetted with water and the brake on the other side operates in normal conditions then an instantaneous difference of even up to 40% in the coefficient of friction between the dry and wet brake may develop, which would then decline during the braking process to about 20%. At the next braking cycle, the coefficient of friction recovers to a value as that of the dry friction pair. At long-lasting wetting, the coefficient of friction in the friction pair drops by about 25% in comparison with that of the same friction pair when dry.

4. Damage to the brake assembly resulting in contamination of the brake disc surface with brake fluid causes the coefficient of friction in the brake friction pair to drop by even 70% and thus significantly reduces the braking torque; in consequence, the vehicle braking performance is dangerously lowered. Such a failure should be immediately detected and indicated to the driver by the on-board diagnostic system.

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