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FULL-SCALE DYNAMOMETER TEST OF COMPOSITE RAILWAY BRAKE SHOES – STUDY ON THE EFFECT OF THE REINFORCING FIBRE TYPE

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Abstract: When designing or developing friction materials, it is crucial to predict how the modification of the formulation will affect their properties. Fibres are introduced in the composition of the phenolic-based brake friction materials to improve their mechanical strength. Apart from reinforcing the composite, fibres can also affect its tribological and thermophysical properties. In this study two composite friction materials are compared. The difference between the materials was the type of reinforcing fibre used in the formulation – in one case it was glass fibre, in the other steel fibre. Thermal diffusivity of both materials was measured and thermal conductivity was calculated. Frictional characteristics determined by means of full-scale dynamometer tests are analysed and discussed. Substitution of glass fibre with steel fibre led to increase in the friction coefficient. Maximum average temperature below wheel surface, observed during the test of the material containing steel fibre, was lower as compared to the test results of the material with glass fibre in its formulation, despite higher heat flux in the course of brake applications. Thermal conductivity of the friction material was enhanced by including steel fibre in the formulation.

Key words: Railway Tread Brake, Friction Material Formulation, Full-scale Dynamometer Test, Thermal Conductivity

1. INTRODUCTION

In railway vehicles equipped with tread brake, composite brake shoes are widely used as friction elements. One of the key factors that contributed to their development in Europe was the effort to supersede cast iron brake shoes and, in consequence, to reduce the rolling noise, which is known to depend on the roughness of the wheel running surface (Petersson and Vernersson, 2002; de Vos, 2016, Yevtushenko et al., 2017). The engineers who design and develop composite friction materials focus mainly on: i) frictional characteristics (coefficient of friction and wear of the friction pair), ii) material properties, iii) impact on the environment and iv) production cost. To fully characterise the friction material, it is important to determine thermophysical properties, such as thermal conductivity and heat capacity. These properties have an effect on the partition of frictional heat.

In the design and development process of friction materials, it is crucial to predict how the modification of the formulation will affect properties of the composite. Due to a large number of constituents, the relations between tribological, mechanical and thermophysical properties of the friction material and its formulation are very complex. This knowledge is quite often qualitative rather than quantitative and of empirical nature (Kim et al., 2001; Singh et al., 2017). Published literature concerning modification of the formulation of brake friction materials is discussed in more detail in (Wasilewski, 2017). Vast majority of the studies is focused on formulations for automotive applications.

Manufacturers of brake systems verify the selection of the friction pair on the full-scale dynamometers, i.e. with friction elements in their natural size. In such test procedure, operating conditions and route profiles of the designed railway vehicles can be simulated. The determined characteristics of the friction pair are then analysed, e.g. how the coefficient of friction and wear depend on on temperature, sliding velocity, contact force, braked mass etc. The assessment covers also condition of the friction elements, i.e. whether, under given test parameters, evidence of thermal degradation or fracture is detected. In addition, dynamometer testing is an obligatory step in UIC (Union Internationale des Chemins de fer – International Union of Railways) certification procedure (Union Internationale des Chemins de fer [UIC], 2010) as well as in assessment of conformity procedure, required by European law for brake shoes used in freight wagons (European Commission [EC], 2013; European Railway Agency [ERA], 2015).

Tribological tests, part of the design process of brake friction materials, are also performed on reduced-scale dynamometers. Due to scaling of the friction elements, it is not possible to simultaneously account for their size ratio and simulate all operating conditions from real-life application (Alnaqi et al., 2015; Desplanques et al., 2007). Friction materials used in railway brakes are also tested on pin-on-disc tribometers (Abbasi et al., 2014; Krupa, 2008).

A typical binder in composite brake friction materials – phenolic resin – is brittle, while brake pads and brake shoes are exposed to high compressive and shear forces. Reinforcing fibres were introduced in the formulations quite early in the development of composite friction materials with phenolic binder (Chan and Stachowiak, 2004). For last few decades, manufacturers of brake friction materials have been facing the challenge to find a suitable substitute for asbestos, which is a proven carcinogen (Chan and Stachowiak, 2004). The fibres used in friction materials are, among others: i) glass fibre, ii) metallic fibres, such as steel, brass or aluminium, iii) synthetic fibres, e.g. aramid and acrylic, iv) ceramic fibres, v) mineral fibres, e.g. potassium titanate and sepiolite, vi) carbon fibre and vii) organic fibres, such as cellulose (Bijwe, 1997; Chan and Stachowiak, 2004).

Apart from reinforcing the composite, fibres can also affect its tribological properties, e.g. reduce wear or increase the friction coefficient. It is a common practice to include more than one fibre type so as to improve the desired characteristics (Chan and Stachowiak, 2004).

Phenolic-based brake friction materials are thermal insulators. Fibres characterised by high thermal conductivity, when introduced to the formulation, may increase the amount of heat transferred by the brake pad or brake shoe. The resulting thermal conductivity of the composite depends on i) intrinsic thermophysical properties of its constituents, ii) their concentration, and iii) their geometry and morphology. Thermal conductivity of the composite is improved by a continuous heat conduction path, formed when thermally-conductive particles are in contact (Sim et al., 2005).

Current paper is an extension to the study by Wasilewski and Kuciej (2018). Aim of this work is to investigate the effect of reinforcing fibre on the frictional characteristics of composite railway brake shoe and temperature reached by counter face friction element in the course of the full-scale dynamometer test.

2. EXPERIMENTAL

Two sets of prototype brake shoes were manufactured employing the technology used in mass production. The mixtures, denoted by Material A and Material B, had the same weight concentration of the reinforcing fibre (glass fibre and steel fibre, respectively). Since steel fibre has higher bulk density as compared to glass fibre, its volume concentration was lower. The weight concentration and type of the remaining constituents were identical for both materials. The exact formulation may not be revealed due to its proprietary nature (Tab. 1). Glass and steel fibre were chosen for this study as they differ substantially in their thermophysical and tribological properties, which was expected to have key influence on the frictional properties of the railway brake shoe. Photographs taken with scanning electron microscope (SEM) show the dispersion of the reinforcing fibre in the composite matrix (Figs. 1 and 2). The brake shoes differ in appearance of the friction surface – steel fibre added in Material B is visible as tiny glossy points in Fig. 3b.

Tab. 1. Formulation of the composites

Constituent	Material A	Material B
Glass fibre	25–35 %	0 %
Steel fibre	0 %	25–35 %
Balance	65–75 %	65–75 %

The experimental part of this study concerned full-scale dynamometer test of both composite materials. The test was performed by the Railway Institute in Warsaw, Poland (Instytut Kolejnictwa). Description of the test bench and testing methodology are presented in Konowrocki et al. (2013). In the course of the dynamometer test, normal and tangential force was measured allowing for calculation of the instantaneous coefficient of friction. Temperature was measured by six thermocouples: three of them sliding on the wheel running surface, the remaining three located 2 mm below the contact surface. The examination of the friction materials surface after the dynamometer test was not subject of the current study.

In addition to the dynamometer test, thermal diffusivity of the composites was measured employing the method presented in (Grzes et al., 2016). Using these data, thermal conductivity can be calculated if the density and heat capacity are known. Mechanical and physicochemical properties (including density and heat capacity) as well as results of the reduced-scale dynamometer test of the materials being the subject of this study are presented and discussed in Wasilewski and Kuciej (2018).

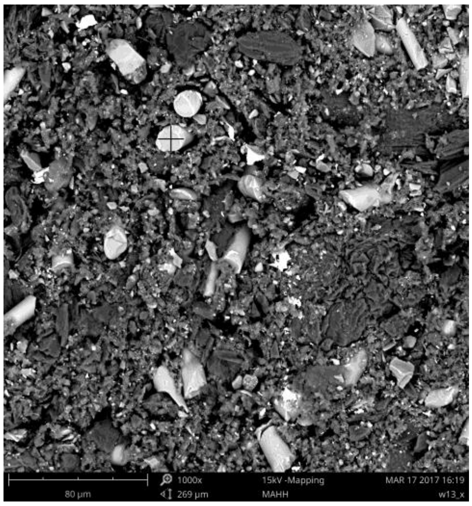

Fig. 1. Dispersion of the glass fibre (marked with a black cross) in the composite (Material A)

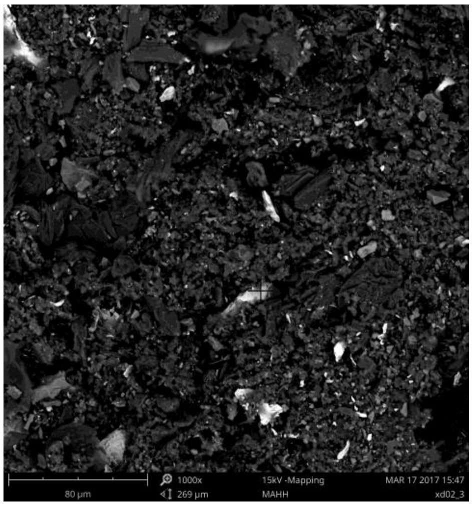

Fig. 2. Dispersion of the steel fibre (marked with a black cross) in the composite (Material B)

The prototype brake shoes before the full-scale dynamometer test are presented in Fig. 3.

The test programme comprised 12 brake applications. The operating conditions are collated in Tab. 2. The test was divided into three sections, each beginning with a brake application with the friction elements at ambient temperature (Tab. 3). In the first section (B1.1–B1.4), no cooling interval between brake applications is specified, apart from the time necessary to accelerate to the subsequent brake application. In the second (B2.1–B2.4) and third (B3.1–B3.4) sections of the programme, cooling period between subsequent brake applications is introduced (120 s and 240 s, respectively).

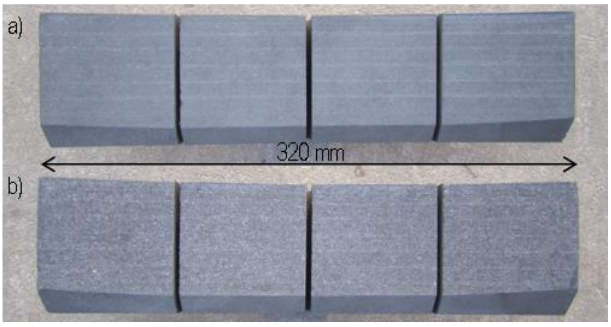

Fig. 3. View of the tested organic composite brake shoes: a) manufactured from Material A; b) manufactured from Material B

Tab. 2. Full-scale dynamometer test parameters

Brake configuration	1xBg
Brake shoe nominal dimensions (length x width x thickness)	320 mm x 80 mm x 60 mm
Wheel material	ER7 steel
Wheel nominal diameter	870 mm
Initial velocity	80 km/h
Nominal contact force	30 kN
Braked mass (per wheel)	7500 kg

Tab. 3. Full-scale dynamometer test programme

Brake application no.	Initial conditions
B1.1	Ambient temperature
B1.2	Acceleration to 80 km/h followed by immediate brake application (no cooling period)
B1.3	Acceleration to 80 km/h followed by immediate brake application (no cooling period)
B1.4	Acceleration to 80 km/h followed by immediate brake application (no cooling period)
B2.1	Ambient temperature
B2.2	Acceleration to 80 km/h, constant velocity maintained for 120 s, followed by brake application
B2.3	Acceleration to 80 km/h, constant velocity maintained for 120 s, followed by brake application
B2.4	Acceleration to 80 km/h, constant velocity maintained for 120 s, followed by brake application
B3.1	Ambient temperature
B3.2	Acceleration to 80 km/h, constant velocity maintained for 240 s, followed by brake application
B3.3	Acceleration to 80 km/h, constant velocity maintained for 240 s, followed by brake application
B3.4	Acceleration to 80 km/h, constant velocity maintained for 240 s, followed by brake application

3. DISCUSSION OF RESULTS

3.1. Thermal diffusivity and thermal conductivity

Results of measurement of thermal diffusivity are presented in Tab. 4. Using the data from Wasilewski and Kuciej (2018), thermal conductivity was calculated as a product of thermal diffusivity, density and heat capacity (Tab. 4). As expected, due to the fact that glass fibre is a thermal insulator and steel fibre is a thermal conductor, Material A has lower thermal conductivity as compared to Material B.

Tab. 4. Thermophysical properties of the composites

Properties	Material A	Material B
Thermal diffusivity	7.013×10^{-7} m^2/s	8.594×10^{-7} m^2/s
Density	1.93 g/cm^3	2.35 g/cm^3
Heat capacity	0.87 J/(g·K)	0.73 J/(g·K)
Thermal conductivity	1.18 W/(m K)	1.41 W/(m K)

3.2. Full-scale dynamometer test results

Results of the full-scale dynamometer test are presented in graphical form in Figs. 4–9. The notation used in the charts is as follows: *Ts* – average temperature measured on the wheel running surface; *Tw* – average temperature measured 2 mm below the wheel surface; *f* – instantaneous coefficient of friction; *v* – velocity. It should be noted, that in order to enhance the readability of the charts, different scale is used in Figs. 4–6 and Figs. 7–9.

Value of the instantaneous friction coefficient of both tested materials is strongly dependent on sliding velocity. In every brake application, in the course of the discussed tests, the coefficient of friction increases as sliding velocity decreases. The initial temperature, in the range which was observed in the analysed tests (approximately 27 °C to 96 °C for Material A and 27 °C to 92 °C for Material B, as measured on the wheel running surface), had no significant influence on the value of the friction coefficient of the tested materials.

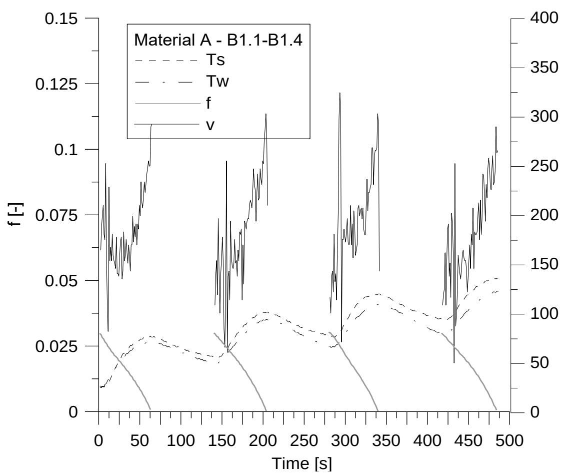

Fig. 4. Results of the first section of the full-scale dynamometer test – Material A

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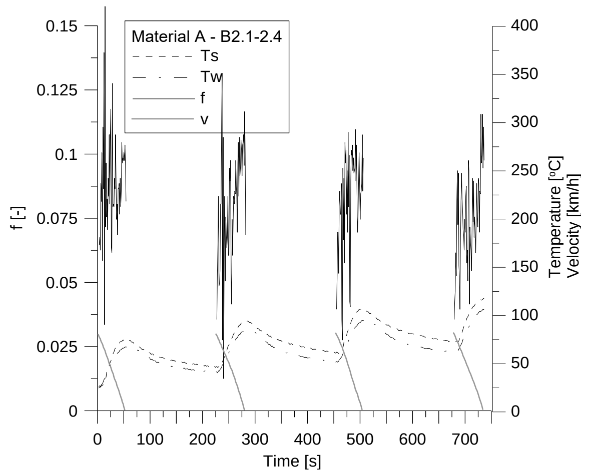

Fig. 5. Results of the second section of the full-scale dynamometer test – Material A

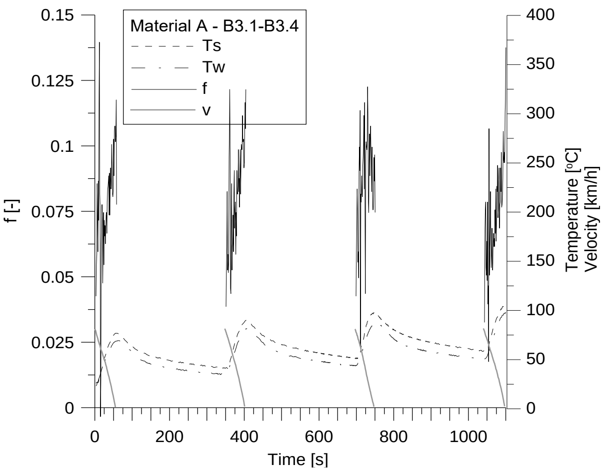

Fig. 6. Results of the third section of the full-scale dynamometer test – Material A

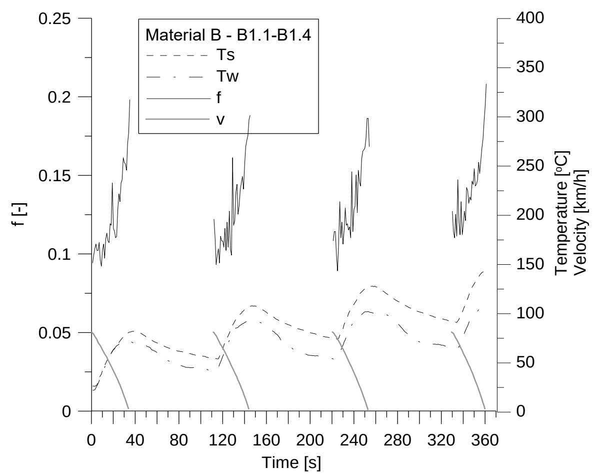

Fig. 7. Results of the first section of the full-scale dynamometer test – Material B

Comparison of the test results shows that Material B is characterised by higher coefficient of friction in relation to Material A. This is consistent with the reduced-scale dynamometer test results presented in Wasilewski and Kuciej (2018). It should be noted, however, that although the tendency is maintained, the values of the coefficient of friction determined by reduced- and full-scale dynamometer test differ. This can be explained by the fact, that frictional characteristics are significantly influenced by the operating conditions.

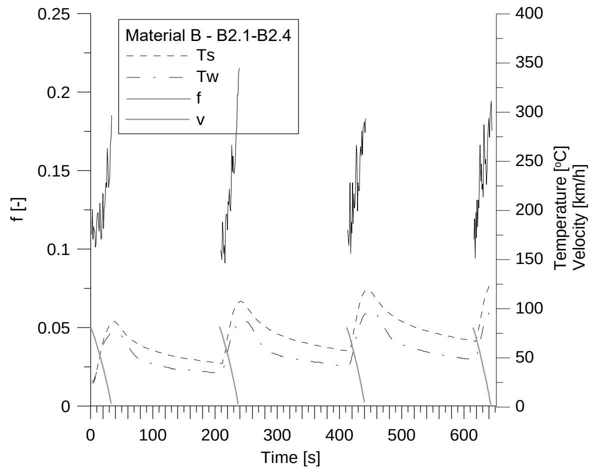

Fig. 8. Results of the second section of the full-scale dynamometer test – Material B

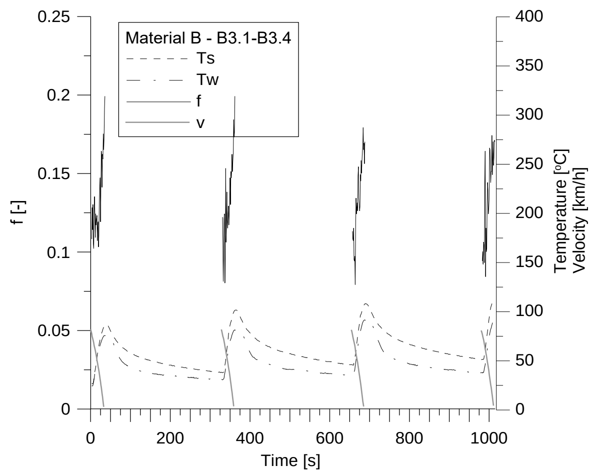

Fig. 9. Results of the third section of the full-scale dynamometer test – Material B

Tab. 5. Maximum average temperature measured during the test

Test programme section	Material A		Material B	
	Ts [°C]	Tw [°C]	Ts [°C]	Tw [°C]
B1.1–B1.4	136.6	123.3	144.4	110.0
B2.1–B2.4	117.5	106.1	126.8	98.8
B3.1–B3.4	106.0	98.2	112.6	91.5

Sincs initial velocity, braked mass and contact force were identical in both tests, lower value of the coefficient of friction resulted in lower heat flux during the test of Material A as compared to the test of Material B. Despite higher heat flux, the maximum average temperature below wheel surface determined in the course of the test of Material B was lower in each section of the test than respective values measured in the test of Material A (Tab. 5). This can be explained by the fact that Material B is a better heat conductor than Material A and in consequence reduces the amount of the heat transferred to the wheel.

The average maximum temperature on the wheel running surface measured during the test of Material B was higher than respective values in the test of Material A. The higher radial temperature gradient in the test of Material B may be the result of the shorter duration of the brake applications – in the case of Material A, the brake applications lasted between 52 s and 68 s, while in the case of Material B, the brake applications lasted between 30 s and 35 s.

4. CONCLUSIONS

Thermal conductivity of the friction material can be enhanced by including steel fibre in the formulation. In consequence this leads to reduction of the amount of heat transferred to the counter face friction element. This change in formulation has, however, a significant effect on the frictional properties of the composite. Substitution of glass fibre with steel fibre increases the coefficient of friction – for the analysed composites and test conditions, its value was approximately two times higher. Since friction level and wheel temperature are among the most important criteria in assessment of the properties of composite brake shoes, it may be concluded that the friction material which contains steel fibre is more suitable for application in railway vehicles.

In the next step of the work planned by the author, the data collected in the experimental test, namely instantaneous coefficient of friction and measured temperature evolution, will be used to verify the finite element model of the frictional heating of railway tread brake.

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