EFFECT OF ULEXITE AND CASHEW ON THE WEAR AND FRICTION CHARACTERISTICS OF AUTOMOTIVE BRAKE PAD

I. SUGOZU[a], I. MUTLU[b]*, A. KESKIN[c]

[a] *Department of Automotive Engineering, Tarsus Technology Faculty, Mersin University, 33200 Mersin, Turkey*
[b] *Department of Automotive Engineering, Technology Faculty, Afyon Kocatepe University, 03200 Afyonkarahisar, Turkey*
E-mail: *ibrahimmutlu@aku.edu.tr*
[c] *Automotive Programme, Bolu Vocational School, Abant Izzet Baysal University, 14500 Bolu, Turkey*

ABSTRACT

The aim of the current research is to investigate as a new automotive friction material using together ulexite and cashew on the brake pad for braking performance. Therefore, newly formulated brake pads have been produced using ulexite and cashew. Tribological properties of the friction materials were obtained using brake test equipment. The variation of friction coefficient, the temperature of friction surface and amount of wear were examined to assess the performance of these samples. In addition, micro-structural characterisations of braking pads were carried out using Scanning Electron Microscopy (SEM). Results showed that the friction materials containing ulexite and cashew have an important effect on friction stability and fade resistance. The strategy proposed in this paper can be considered as alternative friction materials of ulexite, and cashew can be used as friction materials in the brake pads.

Keywords: brake pad, composite materials, friction coefficient, ulexite, cashew, tribology.

AIMS AND BACKGROUND

The performance of a brake system in a vehicle is mainly determined by the tribological characteristics of a friction couple, which is composed of a gray iron disk (or drum) and friction materials[1,2]. A main important property of friction materi-

* For correspondence.

als is to have high friction coefficient and remain stable under enforcement and especially at high temperatures[3,4]. Function of the brakes is to change the kinetic energy into heat energy by absorbing and spreading it to the atmosphere. If generated heat is more than brake capacity, there will be a friction coefficient decrease in brake pads. When brake pads are exposed to high temperatures for long time, they will be damaged. This damage results in a decrease in brake performance, high brake pads wear or sound[4,5]. Therefore, a great deal of effort has been given to develop friction materials having optimised tribological characteristics regardless of various braking conditions[1,2].

Brake pads that are currently used in industry can contain four classes of ingredients: binders, fillers, friction modifiers, and reinforcements[6]. These ingredients also contain a large number of different constituents like ceramic particles and fibres, minerals, metallic chips, solid lubricants and elastomers in a matrix material such as phenolic resin. A description of more than 100 formulations of patented friction materials can be found in Ref. 7. In a simplistic sense, fibres are included for their friction properties, heat resistance, and thermal conductivity. The physical and chemical properties of the resin affect the wear process and friction characteristics of the friction material[8]. Numerous compositions of friction materials have been developed, largely by empirical testing[9,10]. Several projects were conducted to investigate friction materials that could improve the braking effectiveness while also contributing to energy efficiency[11]. In the literature, there are a lot of studies about using new material for the brake pads in order to increase braking performance[12–18].

Raw and refined borates are used in ceramic glazes; the thin coatings are applied onto ceramics. Borates are consumed mostly in glass and fibreglass industry. Borates help glass formation, reduce thermal expansion and give resistance and durability to the ceramics. The addition of borates reduces material stresses caused by temperature gradients, thus making it more resistant to breaking. Borates are also used in borosilicate glasses. Borosilicate glass is not only highly resistant to chemical attack, but it also has a very low coefficient of thermal expansion and, as a result, a high resistance to thermal shock. This thermal shock resistance exceeds that of ordinary glass by a factor of three[19]. Ulexite is a mineral that combines calcium, sodium, water molecules, and boron in a complicated arrangement with the formula $NaCaB_5O_9.8H_2O$. It consists of thin crystals that act like optical fibres. On the surface, ulexite takes the shape of soft-looking masses and is often called ‘cotton ball’. It also occurs beneath the surface in veins similar to chrysotile, in which the crystal fibres run across the thickness of the vein[20].

Cashew friction dust is made out of CNSL (cashew nut shell liquid). The friction particles is used as a stability agent in brake products and it has got a resilient nature, and act as a cushioning agent of the engaging property of the pad. Further it is easily decompose on the surface able brake pad at various elevated temperature controlling the wear and acting as a protective device by prohibiting the excessive temperature being generated. It also easily absorbs the heat and disperses the same in the whole area of friction material. It is mainly use as on of the prime raw material for heavy automobile non-asbestos and asbestos brake pad. It is also used in clutch facing and disc pad[21,22].

In order to test the performance of ulexite in automotive friction materials, ulexite is sifted after grinding to obtain dust as raw boron products. Ulexite and cashew together are used, when rate of ulexite is increased, rate of cashew is decreased. Five kinds of specimens are designed having different ingredients. Tribological properties of these samples were obtained using brake test equipment. The friction tests were performed up to 400°C. The variation of friction coefficient, the temperature of friction surface and amount of wear were examined to assess the performance of these samples. In addition, micro-structural characterizations of the braking pads were carried out using Scanning Electron Microscopy (SEM). Results showed that the friction materials containing ulexite have an important effect on friction stability and fade resistance. Due to resistance to heat of the ulexite, durability to the ceramics and ability to reduce the thermal expansion, the using of this material in brake pads can be attractive.

EXPERIMENTAL

In this study, a new automotive brake friction material was developed by using additive ulexite. The performance of ulexite on brake friction characteristics was especially examined. Friction materials investigated in this study were a non-asbestos organic (NAO) type material containing different ingredients including ulexite. Ulexite is obtained from Balıkesir, Bigadiç mine of Etibank in Turkey. The composition of ulexite studied in this work is shown in Table 1.

In the present work, five different samples were produced. These specimens contain ulexite, phenolic resin, steel fibre, copper, aluminium oxide, graphite, brass particles, cashew and barite. The friction coefficient and temperature values were stored in a databank. Friction coefficient-time and temperature-time graphs and mean coefficient of friction are obtained to identify friction characteristic.

An analytical balance was used to weigh the ingredients. Friction material specimens were produced by a conventional procedure for a dry formulation following dry-mixing, pre-forming and hot pressing. These ingredients were then mixed for 10 min using a commercial blender. The final mixture was loaded into an inch square (small samples) mold for pre-forming under pressing at a pressure of 9.8 MPa. Pre-formed samples were put in hot pressing mold and under pressing at a pressure of 14.7 MPa and 180°C for

Table 1. The composition of ulexite studied

Element	B_2O_3	CaO	Na_2O	SiO_2
%	24–38	18–24	2–7	4–13

Table 2. Ingredients of samples (wt.%)

	Specimens Code				
	UC-4	UC-8	UC-12	UC-16	UC-20
Phenolic Resin	22	22	22	22	22
Steel fibre	15	15	15	15	15
Al_2O_3	3	3	3	3	3
Brass particles	5	5	5	5	5
Graphite	3	3	3	3	3
Barite	20	20	20	20	20
Cu particles	8	8	8	8	8
Cashew	4	8	12	16	20
Ulexite	20	16	12	8	4
Total	100	100	100	100	100

15 min. During the hot pressing process, pressure was released several times to release the gases that evolved from the cross linking reaction (polycondensation) of the phenolic resin. Detailed conditions for each manufacturing step can be found in Ref. 23. The composition of the friction materials studied in this work is shown in Table 2.

In this study, in order to define friction coefficients of automotive brake pad under different temperatures, a test device was designed and manufactured. Figure 1 shows schematic view of the brake tester used in this study.

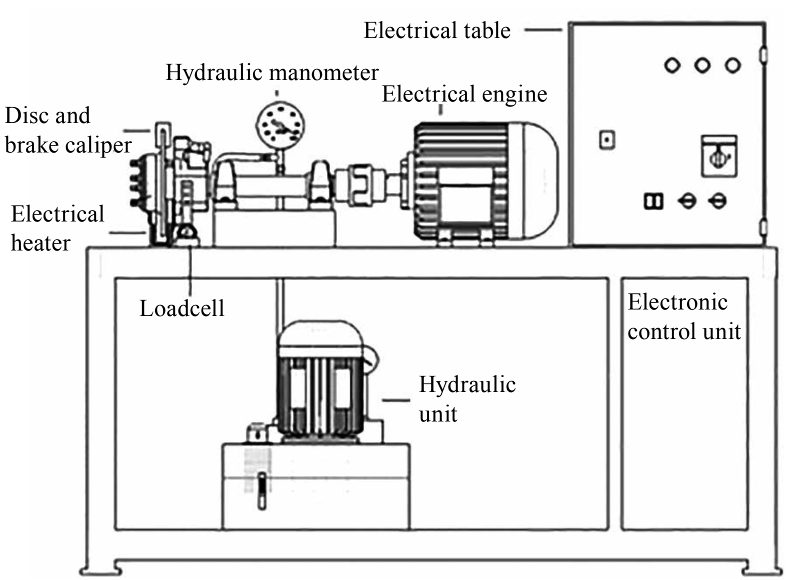

Fig. 1. Schematic view of the brake tester

Using a real brake disc type tester, the friction coefficient characteristics of the pad next to the disc made of cast iron were investigated with changing the pad. The test sample was mounted on the hydraulic pressure and pressed against the flat surface of the rotating disc. Before performing the friction coefficient test, the surfaces of the test samples and the cast iron discs were ground with 320-grid sandpaper. The normal load was varied to achieve a constant friction force. Braking tests were carried out at 1.05 MPa pressure, 6 m s^{-1} velocity and at temperatures from 50 to 400°C for 500 s. An electrical heater was used in order to achieve 400°C in friction surface temperature. The temperature and friction coefficient values were stored in a databank. The tests were repeated three times for each sample. Friction coefficient-time and temperature-time graphs are obtained to identify the effect of these variables. Friction coefficient of surface material couple needs to be high and stable. The friction coefficient was calculated by measuring normal and tangential pressures throughout 500 s test. It is expressed as a mean value of entire braking dependence during the friction coefficient test. Specific wear rate is determined by the mass method following the Turkish Standard (TS 555) and British Standard (BS AU142) and calculated by the following equation:

$$V = \frac{(m_1 - m_2)}{L\ f_m \rho}$$

where V is specific wear (mm^3/MJ), m_1 – mass of brake pad before testing (kg), m_2 – mass of brake pad after testing (kg), L – friction distance calculated by using the number of revolution and radius of the disc (m), f_m – average friction force (N), ρ – the density of brake pad (kg/mm^3) (Refs 24 and 25).

RESULTS AND DISCUSSION

Effect of temperature on friction performance. In the present study, 5 specimens were used. These specimens contain copper particles, phenolic resin, Al_2O_3, steel fibre, brass particles, graphite, barite, ulexite and cashew (Table 2). These samples include 4–20% ulexite and 20–4% cashew, and mean of friction coefficient is ranging from 0.39 to 0.44.

When the coefficient of friction (μ) is concerned, it varies significantly at the initial stage of testing. This can be attributed to the fact that the size of the contact area increases and the friction layer is developed on the surface. In order to determine, the variations of the friction coefficient and temperature of friction surface with test time of the samples were performed at the applied temperature from 50 to 400°C (Figs 2 and 3).

As seen from these figures, the friction coefficients show different features depending on the content. Generally, the friction coefficient value gradually in-

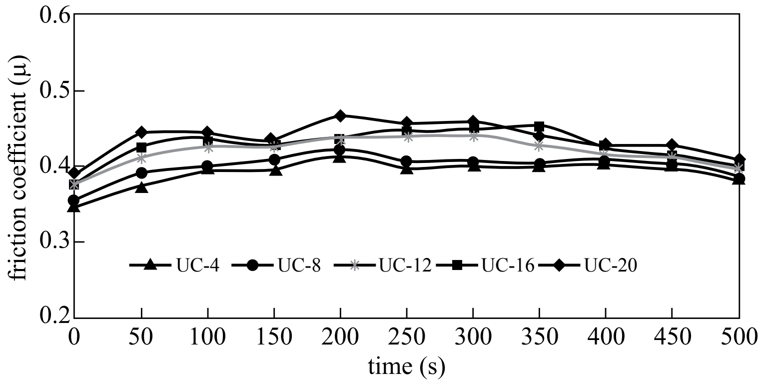

Fig. 2. Variation of friction coefficient as a function of time for samples

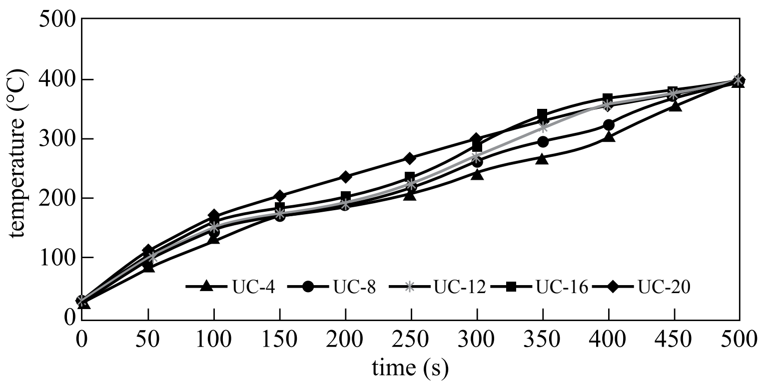

Fig. 3. Temperature as a function of time for samples

creases for all samples until 100th s and then gradually decreases after 400th s (Figs 2 and 3). The reason of increasing friction coefficient is contact of the metallic material to the disc surface. The metallic materials in ingredient wear test during. Therefore, these metallic materials detach from surface of brake pad, and the friction coefficient decreases. This phenomenon is continuing until new friction surfaces occur. Rapid increase in coefficient of friction may lead to a rapid increase in temperature on the surface of friction.

It was found that the friction coefficient decreases with increasing testing temperature. Generally, friction coefficient decreased between 350 and 400°C due to softening of phenolic resin (Figs 2 and 3). As a result, fading occurred during the brake action. Furthermore, with the increasing temperatures, the ingredients in the braking pad are affected from each other due to faster diffusion. This phenomenon is called thermal fade[2]. Therefore, one can say that the present samples are only until temperatures 400°C.

There is an increase in μ until 200th s, and degrades slightly after 350th s where μ kept almost constant in UC-4 and UC-8 samples (Fig. 2). This degradation is somewhat slow with slight fluctuations. Until 300th s, as a result of friction, almost the temperature of 300°C is achieved on the friction surface. The friction coefficient of UC samples decreased due to the increase in temperature[26].

Nonetheless, it should be noted that good stability of μ is achieved using samples under the working condition considered. These results are consistent with the behavior of friction coefficient of all of samples. Therefore, if a μ value between 0.39–0.44 is desired, ulexite and cashew together can be used in brake pads with 4–20% weights as additive. Furthermore, if stability is desired in μ, and μ has higher values, UC-20 coded samples are suggested as better material for brake pads when compared to others. Some middle vibrations and noise were observed during testing in the friction assessment and screening test (FAST). This vibration was typically observed at the beginning of the test before a stable friction layer was developed.

Microstructural characterization of friction surfaces. Apparently, the friction layers are formed by the wear particles generated during friction. The chemistry and structure of a friction layer depend on bulk materials (pad and disc), testing conditions and environment. The role of the friction layer may vary depending on its characteristics[27,28]. The SEM micrographs of the braking pad surfaces after the braking test are illustrated in Figs 4 to 8. The friction surfaces of the samples were characterised using the SEM (LEO 1430 VP). The sample surfaces for the SEM observations were always coated with carbon. There are micro-voids on the surface of almost all samples. Micro-voids consist of falling of the metallic particles during the friction. It is seen from Fig. 5 that larger micro-voids occurred

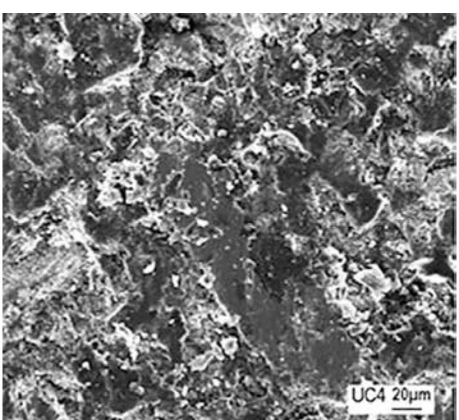

Fig. 4. SEM micrographs of brake pad specimens for UC-4

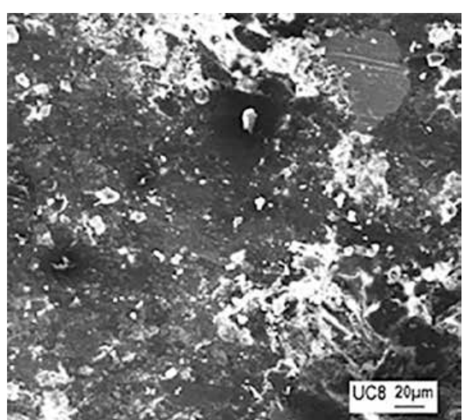

Fig. 5. SEM micrographs of brake pad specimens for UC-8

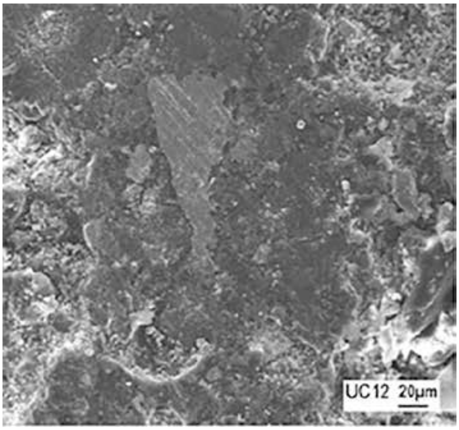

Fig. 6. SEM micrographs of brake pad specimens for UC-12

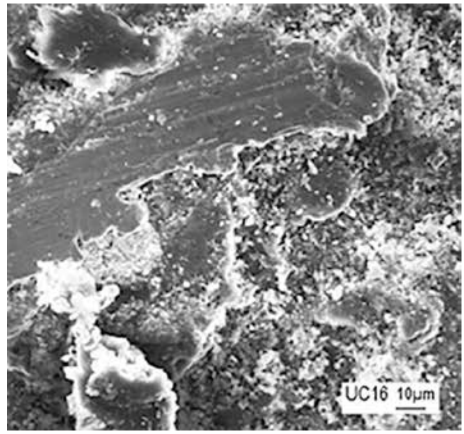

Fig. 7. SEM micrographs of brake pad specimens for UC-16

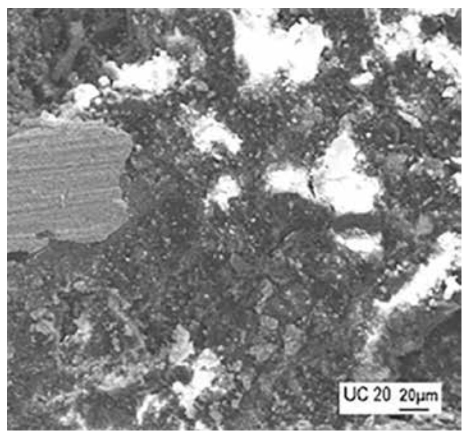

Fig. 8. SEM micrographs of brake pad specimens for UC-20

in the samples due to detaching metallic particles. As seen in figures, some particles are detached from the body causing micro-voids. The micro-voids on the surface of the samples can be classified as smaller and bigger size. The bigger sized micro-voids are due to pitting of the metallic particles during the friction. The worn metallic particles imply that they actively participated in friction during braking test. It is known that if the metal-component coherent surface is bigger; friction and wear will be increased. In addition to micro-voids, there are some micro-cracks on the surface. It is also observed that Al_2O_3 particles are distributed in homogeneous and therefore they stayed as affective in friction surface.

In the present work, several characteristic features can be observed on the friction surface of pads. It is seen as white points in Figs 5 and 8. Also the dark areas can be seen in Fig. 5. Less intimate contact on the trailing edge facilitates the access of air and uneven wear related to a higher oxidation (burn-off) of phenolic resin. This is due to distribution of the friction force over the pad surface[28]. When the pads heated up during braking, the resin tended to expand and at very high temperatures; and the resin turns into glassy carbon. Carbonised resins weaken the matrix and accelerate pad wear (Figs 5 and 7) (Refs 28 and 29. The glassy phase lost support and was torn off from the surface by shear force[30]. Figures 6, 7, and 8 (from the SEM) show a thick friction layer developed on the surface of pads. In this particular case, the friction layer covering the friction surface diminishes the abrasive effect of the glassy phase by eliminating the sharp edge of the glass and smoothing the friction surface. Hard glassy particles typically act as an abrasive element, and scratch off the cast iron disc counter face and the material adhering to it[28]. Apparently, the carbonaceous matrix was formed of graphite, coke and degraded phenolic resin. The ingredient having the plastic deformation capability has taken a flake like feature after the friction experiment (Figs 7 and 8).

All matters were homogeneously distributed in the matrix and therefore, very few micro voids were observed in the structure (Figs 4, 5, and 6). The friction process is characterised by the development of friction debris. Such debris adheres to the friction surface and forms a friction layer easily visible from an inspection of the sample surface after testing in the FAST (Figs 7 and 8). Systematic analysis of the surface of composite materials indicated that the friction process dominantly occurred on the friction layer, which eventually covered the top of the bulk. The presence of a well-developed friction layer on the friction surface as well as its morphology is easily visible. A detailed view of the friction surface including the information about the friction layer is shown in Figs 4 to 8. Diffusion is occurred in the Cu particles located in the friction layer. Brighter areas marked as Cu in Figs 4, 5, and 7 represent the regions where the Cu is interacted in the friction layer[31].

Wear behaviour. Table 3 gives the mean coefficient of friction, the standard deviation of coefficient of friction, density, hardness and specific wear rate of the tested samples. As can be seen from Table 3, the friction coefficients are in appropriate category according to Turkish Standard TS 555 and British Standard BS AU142. Also the standard deviation is very small, which means that the material has a stable friction characteristic.

In the present study, a direct proportionality was not found among density, hardness, and wear resistance due to the complexity of composite structure. However, the highest friction coefficient is obtained for the sample having UC-20

Table 3. Typical characteristics of the brake pad used

Sample code	Mean coefficient of friction	Standard deviation	Density (g cm^{-3})	Hardness (Brinell)	Specific wear (g mm^{-2})
UC–4	0.394	0.0182	1.935	18.2	0.26×10^{-6}
UC–8	0.401	0.0172	1.842	16.2	0.27×10^{-6}
UC–12	0.420	0.0192	1.765	15.9	0.34×10^{-6}
UC–16	0.427	0.0216	1.704	14.7	0.37×10^{-6}
UC–20	0.437	0.0223	1.680	13.9	0.38×10^{-6}

content. This sample includes 4% ulexite and 20% cashew. The lowest friction coefficient is obtained for the sample having UC-4 content. This sample includes 20% ulexite and 4% cashew. In addition, less wear is observed at the UC-4 sample. The mean of friction coefficient is ranging between from 0.39 to 0.44 (Table 2). These results are consistent with the earlier works[32–35].

As can be seen from Table 3, the friction coefficient achieved for sample UC-20 is approximately 0.44 and higher which are considered to be very good when compared to coefficients of friction achieved in current brake pads. UC-4 coded sample has the highest density and hardness in all specimens. It is included in 20% ulexite and 4% cashew; the specific gravity of ulexite is bigger than of cashew. The more ulexite rates the more density.

It is well known that friction coefficient is usually associated with an increase of wear. In the present work, all samples supplied that kind of result (Table 3). But UC-16 and UC-20 coded specimens have better values than the other specimens. Therefore, one can say that only the specimens of UC-16 and UC-20 are preferred for that kind of brake pad due to all providing the better mechanical and microstructural properties than the other specimens.

It can be seen from the results that there is no a direct correlation between wear resistance and hardness. However, nevertheless this is an unavoidable reality of these features that affect each other. As can be seen from the table, high hardness pad has high wear resistance and less wear due to content of component samples forming. Component of pad materials comprising the compounds of different content can have a hard structure and, the outcome is higher hardness values. But the amount of resin component which constituent materials are not sufficient or particle adhesion surface decreased, quickly separation of particles that make up the main structure at slight strains while friction can wear rate higher than expected.

The mean coefficient of friction, hardness, and wear rates of the samples showing parallelism to each other exhibit the characteristics of the material. The sample having a high mean coefficient of friction has a high wear rate also. In this case, rubbing the ruptures of large particles from brake pad by the effect of strain has a significant impact. Also, since the pad hardness is lower than the hardness of the disk, the more wear naturally would be at the process of creating a high coefficient of friction[36].

CONCLUSIONS

In this study, the effect of ulexite and cashew content on the friction and wear behaviour of brake pad used in automotive industry is experimentally analysed. As a result of experiments, structure and chemical composition of the friction layer generated on the friction surface significantly differed from the bulk. It is apparent that no simple relationship exists between composition of the friction layer and bulk material formulation.

The highest friction coefficient is obtained for UC-20 specimen. The smaller values are obtained for the other specimens. The UC-8 coded specimen have more stable friction coefficient during FAST test than other samples. While the UC-4 and UC-8 coded specimens provided lower friction coefficients, their wear ratios and standard deviations were considerably lower. The sample of UC-20 performed better friction and wear properties within 5 samples. Therefore, this specimen can be suggested as brake pad material.

In the present work, the standard deviation is in the acceptable range for all specimens. No direct proportionality among mean coefficients of friction, the standard deviation and wear resistance could be found due to the complexity of composite structure. Some micro-voids and micro-cracks are observed on the worn surface.

ACKNOWLEDGEMENTS

This research is funded by the Scientific and Technological Research Council of Turkey (TUBITAK) (Grant Reference No 106M006). The authors wish to acknowledge the TUBITAK and our partner organisations for their support.

REFERENCES

1. M. G. JACKO, S. K. LEE: Brake Linings and Clutch Facings. In: Kirk–Othmer Encyclopedia of Chemical Technology, Vol. 4, 1992, 523–536.
2. A. E. ANDERSON: Friction, Lubrication, and Wear Technology. ASM Handbook, ASM International, **18**, 569 (1992).
3. M. BOZ, A. KURT: Relationship Between Density and Friction Coefficient in Powder Metal Bronze Brake Lining. In: Proceedings of the Second International Conference on P/M, Cluj-Napoka, Romania, 6–8 July 2000, 1, 181–87.
4. M. BOZ, A. KURT: Wear Behaviour of Organic Asbestos Based and Bronze Based Powder Metal Brake Linings. Materials and Design, **26**, 717 (2005).
5. E. W. REINSCH: Sintered Metal Brake Linings for Automotive Applications. Delco-Moraine Division, General Motors Corp Dayton, **2**, 9 (1970).
6. J. BIJWE: Composites as Friction Materials: Recent Developments in Non-Asbestos Fibre Reinforced Friction Materials a Review. Polymer Composites, **18** (3), 378 (1997).
7. P. J. BLAU: Compositions, Functions, and Testing of Friction Brake Materials and Their Additives, Oak Ridge National Laboratory, Department of Energy, Tennessee, U.S.A., 2001, 37831-6285.
8. H. JANG, S. J. KIM: The Effects of Antimony Trisülfide (Sb_2S_3) and Zirconiumsilicate ($ZrSiO_4$) in the Automotive Brake Friction Material on Friction Characteristics. Wear, **239**, 119 (2000).

9. P. J. BLAU: Compositions, Functions, and Testing of Friction Brake Materials and Their Additives. Oak Ridge National Laboratory Technical Report ORNL/TM 2001/64, Oak Ridge, Tennessee, 2001, 24.
10. G. NICHOLSON: Facts About Friction. Gedoran Publishing, Winchester, VA, 1995, 260.
11. S. ÖZCAN, P. FILIP: Microstructure and Wear Mechanisms in C/C Composites. Wear, **259**, 642 (2005).
12. B. ÖZTÜRK, S. ÖZTÜRK: Effects of Resin Type and Fibre Length on the Mechanical and Tribological Properties of Brake Friction Materials. Tribology Letters, **42**, 339 (2011).
13. İ. SUGÖZÜ, İ. MUTLU: Investigation of the Effect of Waste Tire Rubber on Friction Behaviour in Automotive Brake Linings. J. Theor. Appl. Mech. Sofia, **39**, 101 (2009).
14. İ. MUTLU: Investigation of Tribological Properties of Brake Pads by Using Rice Straw and Rice Husk Dust. J. Appl. Sci., **9** (2), 377 (2009).
15. A. C. DRUMEANU, N. N. ANTONESCU, R. G. RIPEANU: Some Aspects Concerning the Experimental Determination Methodology for the Non-isothermal Cyclic Durability of the Machine Steels. J Balk Tribol Assoc, **16** (3), 315 (2010).
16. K. W. LIEW, U. NIRMAL: Frictional Performance Evaluation of Newly Designed Brake Pad Materials. Materials & Design, **48**, 25 (2013).
17. A. C. DRUMEANU, R. G. RIPEANU: Metallic Element Design of the Tribo-thermal Stressed Dry Friction Couples. J Balk Tribol Assoc, **16** (3), 362 (2010).
18. A. KESKIN: Investigation of Using Natural Zeolite in Brake Pad. Scientific Research and Essays, **23**, 4893 (2011).
19. http://www.boren.gov.tr (10.09.2013)
20. R. B. KISTLER, C. HELVACI: Boron and Borates. Industrial Minerals and Rocks, 171 (1994).
21. J. BIJWE, N. M. NIDHI, B. K. SATAPATHY: Influence of Modified Phenolic Resins on the Fade and Recovery Behavior of Friction Materials. 15th International Conference on Wear of Materials, Wear, **259**, 1068 (2005).
22. A. GANGULY, R. GEORGE: Asbestos Free Friction Composition for Brake Linings. Bulletin of Materials Science, **31**, 19 (2008).
23. İ. MUTLU: Investigation of Some Ceramic Additive Automotive Brake Pads, PhD thesis, University of Sakarya, Turkey, 2002.
24. TS 555 (Turkish Standard). Highway Vehicles, Brake Systems, Brake Pads for Frictional Brake, Turkey, 1992.
25. British Standards Specification: BS AU 142–1968.
26. G. P. OSTERMEYER: On the Dynamics of the Friction Coefficient, Wear, **254**, 852 (2003).
27. M. ERIKSSON, F. BERGMAN, S. JACOBSON: Surface Characterization of Brake Pads After Running Under Silent And Squealing Conditions, Wear, **232**, 163 (1999).
28. K. W. HEE, P. FILIP: Performance of Ceramic Enhanced Phenolic Matrix Brake Lining Materials for Automotive Brake Linings. Wear, **259**, 1088 (2005).
29. A. FISCHER: Well-founded Selection of Materials for Improved Wear Resistance. Wear, **194**, 238 (1996).
30. G. STRAFFELINI: Experimental Observations of Subsurface Damage and Oxidation Wear in Al-based Metal-matrix Composites. Wear, **245**, 216 (2000).
31. İ. MUTLU, İ. SUGÖZÜ, C. ÖNER: Investıgation of Friction Behavior of Boric Acid and Black Pine Cone Dust Added Brake Pads. 5th Int. Adv. Technol. Symp. (IATS'09), Turkey, 2009.

32. T. R. CHAMPMAN, D. E. NIESZ, R. T. FOX, T. FAWCETT: Wear-resistant Aluminum–boron–carbide Cermets for Automotive Brake Applications. Wear, **236**, 81 (1999).
33. S. K. RHEE, M. G. JACKO, P. H. S. TSANG: The Role of Friction Film in Friction, Wear and Noise of Automotive Brakes. Wear, **146**, 89 (1991).
34. J. R. BARBER, T. W. BEAMOND, J. R. WARING, C. PRITCHARD: Implications of Thermoelastic Instability for the Design of Brakes. ASME J Trib, **107**, 206 (1985).
35. T. MATSUSHIMA, H. MASUMO, S. ITO, M. NISHIWAKI: Fe Analysis of Low-Frequency Disc Brake Squeal (In Case of Floating Type Caliper), SAE–982251.
36. İ. SUGÖZÜ: Production of Non-asbestos Automotive Brake Lining Additional Boron and Investigation of Its Braking Characteristic, PhD thesis, University of Fırat, Turkey, 2009.

Received 9 July 2014
Revised 5 June 2015