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Effect of Glass Powder on the Friction Performance of Automotive Brake Lining Materials

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Abstract:

In this study, bronze-based brake linings containing 0-8 wt% glass powder were manufactured by a hot pressing process and tribological properties of produced samples were investigated using a Chase-type friction tester. The hardness and density of the samples were also determined. The microstructures and friction surfaces of the samples were examined using scanning electron microscopy (SEM). As a result, it was dermined that the sample that was reinforced with 8 wt% glass powder has exhibited the best wear behavior. Furthermore, a reduction in the friction coefficient of all the samples with increasing friction surface temperature was observed. The results have showed that friction coefficient stability of the brake lining samples could be improved with the increasing content of glass powder.

Keywords*: Brake lining materials; Glass powder; Friction coefficient; Hot pressing.*

1. Introduction

The speed and engine power of automobiles have seen a significant increase in the last two decades. Friction materials are therefore required in order to provide a stable friction coefficient and a low wear rate at various operating speeds, pressures, temperatures, and environmental conditions. These materials should also exhibit resistance to heat, water and oil, a high thermal stability, and low noise, causing minimal damage to the brake discs. Lining materials must meet all of these requirements at an affordable cost and with minimum environmental impact [1].

Polymer-based brake lining materials are widely used in the friction brake systems of automobiles and other vehicles. These brake lining materials typically comprise the binders, the lubrication components, frictional additives, and reinforcement elements. The aim of binding is to hold the various components together and form a thermally stable matrix [2-3]. Thermosetting phenolic resins are commonly used as binders, but these are known to decompose at relatively low temperatures (300-400ºC), leading to the generation of frictional heat at an interface [4]. This causes a reduction in the friction coefficient of polymer-based lining materials, thus decreasing road safety [5]. Sintered friction lining materials that exhibit greater wear resistance and a more stable friction coefficient than organic-based brake lining materials are therefore required in order to meet the needs of modern, high-performance cars [6]. These brake linings contain a mixture of metallic binders (copper, iron, aluminum and their alloys), a non-metal compound such as an oxide (Al_2O_3, SiO_2, ZrO_2, mullite and spinel), carbides (B_4C, SiC, TiC and VC), and nitrides (TiN and Si_3N_4) in order to increase the

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coefficient of friction of the brake lining, and solid lubricants (graphite and metal sulphides) [7]. Unfortunately, the relatively high cost of the structural components used to reinforce the matrix material is the major drawback of these brake linings. For this reason, the use of glass powders obtained from waste glass in brake lining materials is proposed, in order to improve their wear-friction properties. Waste glass currently poses a major problem nationwide in terms of disposal or recycling [8-9]. In Turkey, it is estimated that 12000 tons of glass is disposed of every year [10], with most of the non-recyclable glass still being used in landfills. Since this glass is not biodegradable, using waste glass in a landfill does not provide an environmentally friendly solution [9]. This has prompted a desire across various manufacturing fields to utilize this waste glass. The use of waste glass in the production of brake lining materials not only reduces production costs, but also provides an outlet for environmental waste, thus contributing to a sustainable environment.

Although extensive studies on the tribological characteristics of metal-matrix brake lining materials containing reinforcements such as Al_2O_3, $ZrSO_4$, SiO_2, SiC, mullite, and spinel have been conducted [6,7,11-15], studies on the friction-wear characteristics of metal-matrix brake lining materials containing glass powders are rare.

In this study, five bronze-based friction materials containing 0-8 wt% glass powder were produced via the hot-pressing method, and their friction-wear characteristics were investigated according to the SAE J661 standard, using a friction coefficient testing apparatus. The variation in the friction coefficient, mass loss, together with other physical characteristics such as density and hardness, were carefully examined in order to determine the effect of glass powder content on brake lining friction characteristics.

2. Materials and Experimental Procedures

2.1. Sample preparation

The matrix material used to fabricate sintered brake lining materials consisted of 86 % bronze powder (CuPb10Sn10), 11 % iron powder, and 3 % graphite powder. The particle size distributions of the powders are given in Table I.

Tab. I Size analyses of the powders utilized as brake lining materials.

Particles	D10	D20	D90
Iron	36.16 µm	94.08 µm	168.37 µm
Bronze	35.17 µm	91.87 µm	190.83 µm
Graphite	16.23 µm	88.69 µm	206.53 µm
Glass	4.75 µm	28.13 µm	102.77 µm

Tab. II Chemical constituents of glass powder.

Compound	Weight (%)
SiO_2	73.8
CaO	12.5
Al_2O_3	0.834
Fe_2O_3	0.314
Na_2O	9.58
MgO	2.35

Glass powder with an average particle diameter of 28.13 µm was obtained from a glass mosaic producer in Istanbul, Turkey, and added to the bronze matrix material at compositions of 2 wt%, 4 wt%, 6 wt%, and 8 wt%. The chemical analyses of the glass powders used in this study are detailed in Table II. The prepared powders were mixed in a Turbula T2C device for 90 min. This device was able to move in three dimensions during mixing. After the mixing process, the mixture was placed in a 25 mm × 25 mm × 7 mm graphite mold chamber, as shown in Fig. 1, and hot-pressed for 4 min at 650°C with an applied pressure of 70 MPa on an automatic hot-pressing machine.

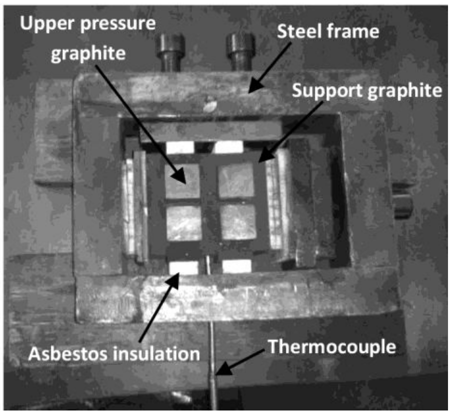

Fig. 1. Powder pressing die used in brake pad sample fabrication.

2.2. Characterization tests

In order to characterize the lining materials produced, after hot-press processing, the density and hardness values of the samples were determined. The densities of the samples were measured using the Archimedes method. The volume percentage of porosity is calculated using $100-\left(\frac{Sintered\ density}{Theoretical\ density}x100\right)$, where the theoretical density of brake lining materials was calculated according to the rule of mixture. Macro-hardness measurements were conducted using a Brinell hardness tester with a 2.5 mm steel ball indenter and a load of 31.25 kg. The morphologies of the worn surface were investigated using a Zeiss/Supra scanning electron microscope. In addition, chemical analyses were conducted using energy dispersive spectroscopy (EDS).

2.3. Performance testing

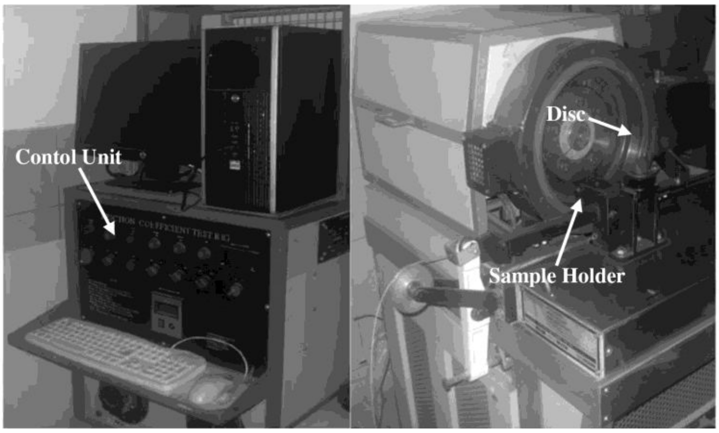

Fig. 2. Chase-type friction material test machine employed in sample testing.

The performance tests included a determination of the friction coefficient, friction stability, wear losses, and types of wear. Performance tests of brake lining materials were conducted using a Chase-type friction tester according to the SAE-J661 standard. As shown in Fig. 2, the tester comprised three main parts: a disc, a control unit, and a sample holder. The performance tests for all samples were carried out using the parameters given in Table III. A cast iron disc with 250 Hv hardness and a 280 mm diameter was used as the wear counterpart in the wear process, in conjunction with brake lining samples with dimensions of 25 mm × 25 mm × 7 mm. Four samples were fabricated for every parameter to be tested, and an average value was calculated from the values obtained. The load applied to the sample was provided by a pneumatic system. The drum temperature was automatically controlled during the test by resistance heaters placed around the outside of the drum and a forced-air cooling system. A computer connected to the tester recorded the test results.

Tab. III Friction performance testing schedule.

Block	Speed (RPM)	Load (N)	On Time (s)	Off Time (s)	Number of applications	Temperature (°C)		
						Min	Max	Increase
Burnish	308	450	1200	0	1	-	93	0
Reset	205	230	300	0	1	-	93	0
Baseline I	411	670	10	20	20	82	104	0
I Fade	411	670	600	0	1	82	289	28
I Recovery	411	670	10	0	4	261	93	56
Wear	411	670	20	10	100	193	205	0
II Fade	411	670	600	0	1	82	345	28
II Recovery	411	670	10	0	5	317	93	56
Baseline II	411	670	10	20	20	82	104	0

Friction coefficient stability was calculated in order to assess variations in the friction coefficients in the 93-345°C temperature range. Friction coefficient stability is defined using the following equation [16].

$$\mu_s = \left[(\mu_{ave}) - (\mu_{max} - \mu_{min}) \times \frac{1}{2} \right] \times \frac{100}{(\mu_{ave})} \qquad (1)$$

where μ_{ave} is the average of the friction coefficient values measured at the following 10 temperature values: 93, 121, 149, 177, 205, 233, 261, 289, 317, and 345°C on the second fade. μ_{min} and μ_{max} are lowest and highest friction coefficient values, respectively, measured at temperatures between 93-345°C.

3. Results and Discussion
3.1. Mechanical Properties

The changes in the density and porosity amount of brake lining materials after the hot-pressing process, as a function of glass powder content are presented in Fig. 3. The porosity values increased as a result of glass powder content. In the literature, it is stated that commercial brake lining materials should have a porosity of up to 12 % in order to maintain sufficient strength at high temperatures [17]. However, porosity values of the samples containing 4 %, 6 %, and 8% of glass powders were found to be 14 %, 16 %, and 18 % respectively. These values are higher than that of the commercial brake lining material. The porosity increases with the increasing glass powder content, which is related to inadequate wetting of it by a bronze matrix. Poor wetting behavior between the glass powder and the bronze matrix also led to an increase in the amount of pores present in the samples as shown in Fig. 4. This results in a material with a lower density. Furthermore, it is of note that the low density of the glass powder compared to that of the bronze-based powder may be another reason for the decrease in the sample density with the increasing glass powder content. Similarly, Okay and Islak (2022) reported that there was a decrease in the densities of produced composite materials with increasing reinforcement rate [18].

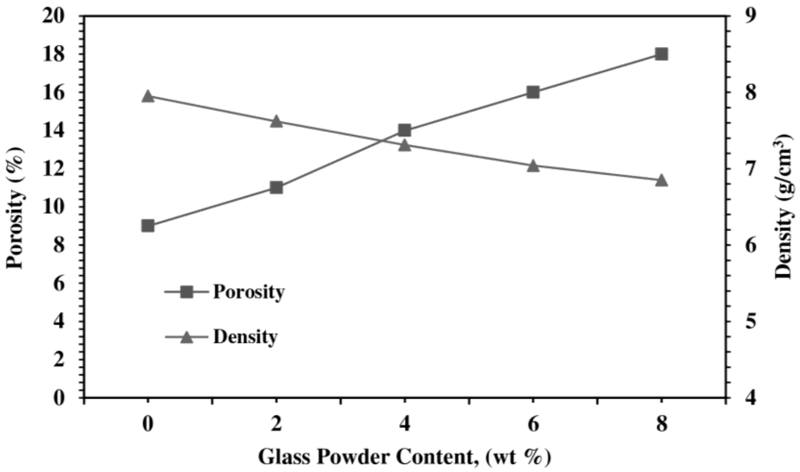

Fig. 3. Effect of glass powder content on the density and porosity of brake lining materials.

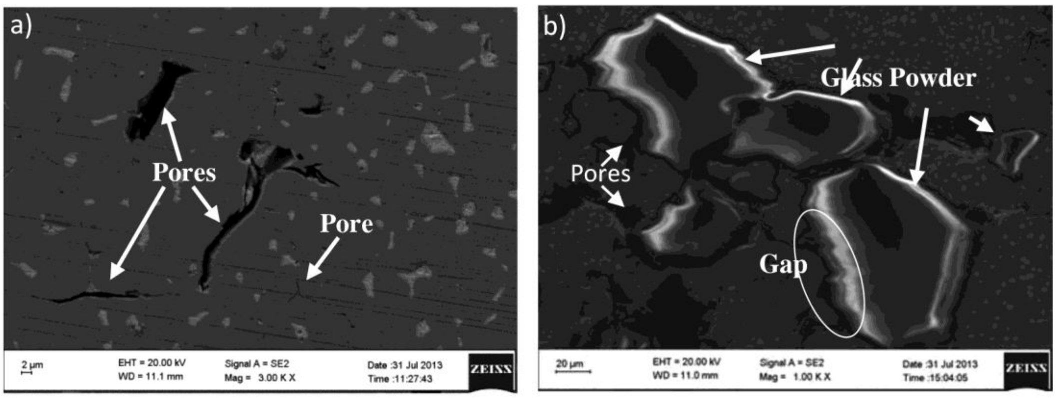

Fig. 4. Micrographs of brake lining materials: a) pure bronze matrix brake lining material (3000×); b) brake lining material containing 6 wt% glass powder (1000×).

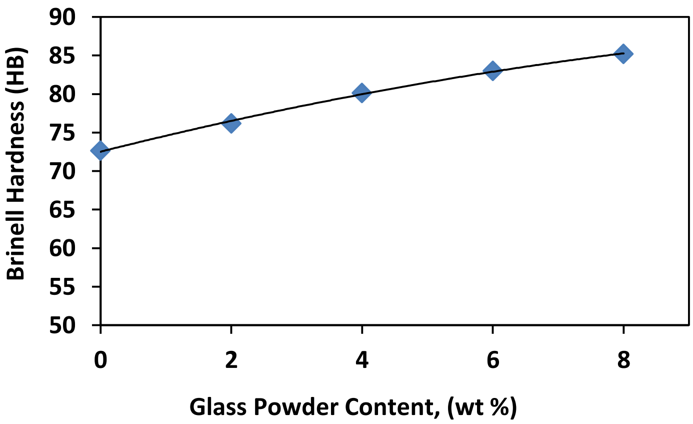

Fig. 5. Effect of glass powder content on the hardness of brake lining materials.

The effect of the addition of glass powders on the hardness of brake lining materials produced via hot pressing is shown in Fig. 5. The hardness values of the brake lining materials containing glass powders are shown to be higher than that of an unreinforced bronze-based brake lining material. This is due to the high hardness value of the glass powder. The presence of the glass powder particles acts as an obstacle to the motion of dislocations, resulting in higher sample hardness compared to the base, unreinforced material [19].

3.2. Friction Performance

The friction characteristics of brake lining materials in contact with a cast iron disc can be explained by the formation of contact plateaus [20-22]. The plateaus are divided into two parts, as primary and secondary plateaus. The primary plateaus consist of the wear resistant components of the lining material, and form nucleation sites for the secondary plateaus. The secondary plateaus are formed by wear debris compaction around the primary plateaus [2,23]. Consequently, the contact plateaus formed on the friction surface of the brake linings are considered to be the main cause of the different friction behaviors exhibited by lining materials [24].

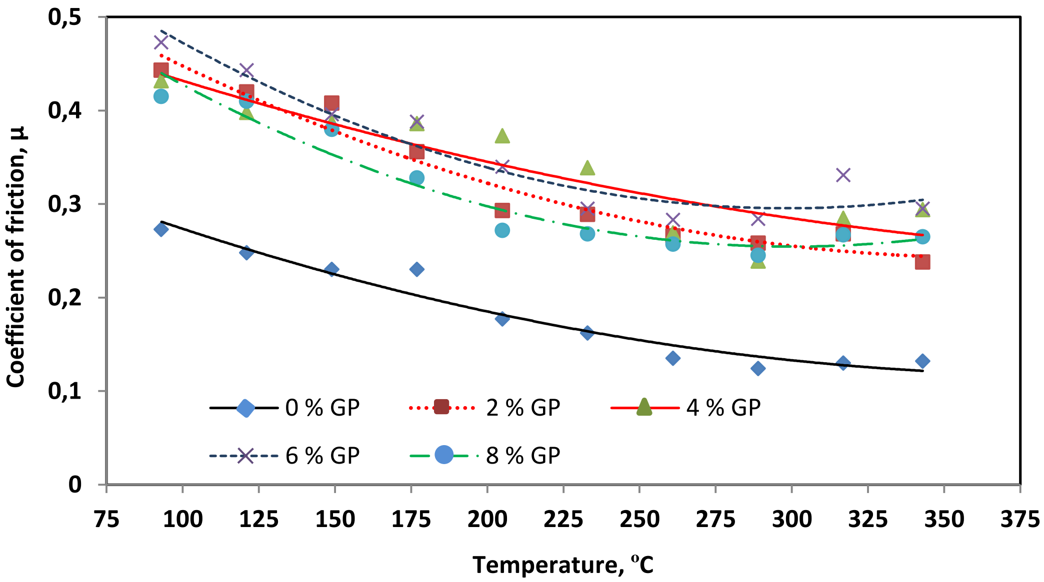

Fig. 6. Effect of glass powder content on variations in the temperature-dependent friction coefficients of the brake lining materials.

One of the most significant requirements for brake lining is that it should exhibit a minimal variation in the friction coefficient with the increasing temperature caused by it during braking [25,26]. The effect of the temperature on the friction coefficients of the brake lining materials is shown in Fig. 6. When Fig. 6 is examined, it is seen that the sample with 2% glass powder added resulted in a friction coefficient of 0.443-0.238, while that of the 8% sample added resulted in a friction coefficient of 0.442-0.294 at a 95-345°C temperature range. This undesirable decrease in the friction coefficient of the brake lining materials with increasing temperature is referred to as "fade". Similarly, Al_2O_3 reinforced bronze-based brake lining materials were also reported to exhibit a decrease in the friction coefficient with the increasing temperature [11]. The fade behavior of the brake lining materials containing the glass powder may be due to the reinforcing glass powders which begin to soften. The temperature of the worn surface is approximately 600ºC during sliding [14]. This temperature is higher than the softening temperature of the glass powder of approximately 540ºC [27].

Hence, the frictional heat generated at the friction interface leads to a decrease in the shear strength between the disk and the glass powder. This in turn leads to a decrease in the friction coefficient with the increasing temperature. Another reason for the reduction in the friction coefficient with the increasing friction interface temperature may be the formation at the point of contact of the oxides that exhibit lubricating characteristics [28,29]. This would then lead to a decrease in the friction coefficient.

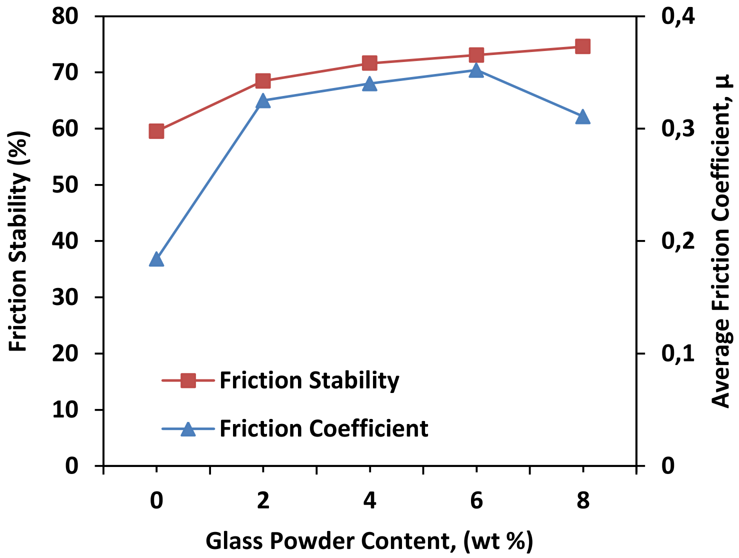

Fig. 7. Effect of glass powder content on friction coefficient and friction stability.

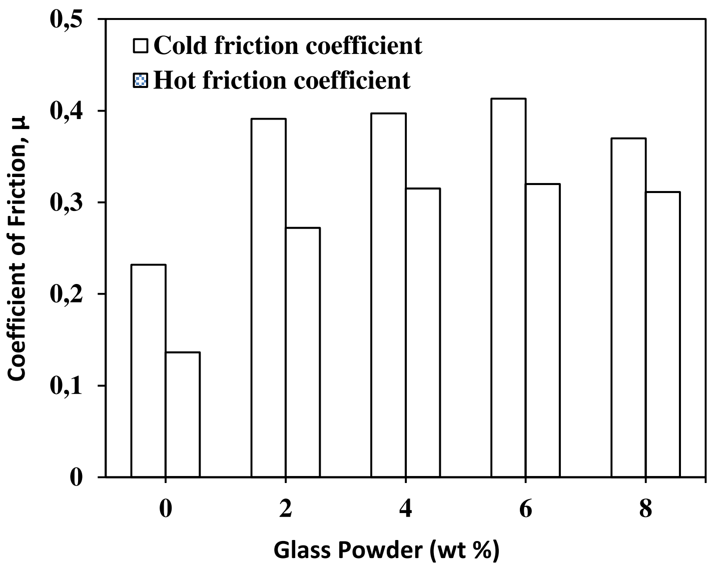

Fig. 8. Effect of glass powder content on the cold and hot friction coefficients of the brake lining materials.

The average friction coefficient values and friction coefficient stabilities of the brake lining materials in the temperature range 93-345°C are shown in Fig. 7. The average friction coefficients of the samples containing glass powder were higher than that of the unreinforced sample. The brake lining sample containing 6% glass powder showed highest average friction coefficient value among all lining samples. When brake lining samples were evaluated in terms of the friction coefficient stability, it was seen that friction coefficient stability increased with the increasing glass powder content. This is because of the formation of the dense contact plateaus on the worn surface of the brake linings. Eriksson et al. [30] explained the stabilized friction coefficient behavior in terms of contact plateaus that occur on the contact surfaces, as shown in the SEM images contained in Fig. 10. The formation of these plateaus, which are defined as contact plateaus by the presence of dense frictional particles, leads to stabilized frictional behavior during braking. Osterle et al. [20] also stated that the formation of a friction film, resulting from wear debris compaction, also plays an important role in stabilizing the friction coefficient of a material during braking.

In this study, the coefficients of friction for the brake lining samples obtained above a particular temperature value (according to the friction-wear test results) are denoted as hot friction coefficients, and those obtained below this value are denoted as cold friction coefficients. Accordingly, the average coefficients of friction obtained during the fade-II test at temperatures of 93, 121, 149, and 205°C are denoted as cold friction coefficients, and the average coefficient of friction obtained at specific temperatures during the recovery-I (205 and 149°C), fade-II (233, 261, 289, 317, and 345°C), and recovery-II (261, 205, and 149°C) tests are denoted as hot friction coefficients. The effect of glass powder content on the cold and hot friction coefficients of the various lining materials is presented in Fig. 8. The hot and cold friction coefficient values increased with increasing glass powder content up to a content of 6 wt %. After this point, the cold and hot friction coefficient values decreased with further increases in the glass powder content. The highest cold and hot friction coefficient values of 0.413 and 0.320, respectively, were obtained for the 6 wt % glass powder reinforced brake lining material, whereas the lowest cold and hot friction coefficient values of 0.232 and 0.136, respectively, were obtained for the unreinforced bronze-based material. It is of note that the hot friction coefficient values were always lower than the cold friction coefficient values for glass powder reinforced samples. This may be due to the fact that glass powder has a low softening temperature. Frictional heat generated during braking leads to a blunting of the glass powder, caused by the softening of the glass powder at low temperatures. Therefore, the hot friction coefficient is lower than the cold friction coefficient. Supporting this idea, Kim et al. [31] was reported that there was a drop in friction coefficient values due to a blunting of the abrasives in the system.

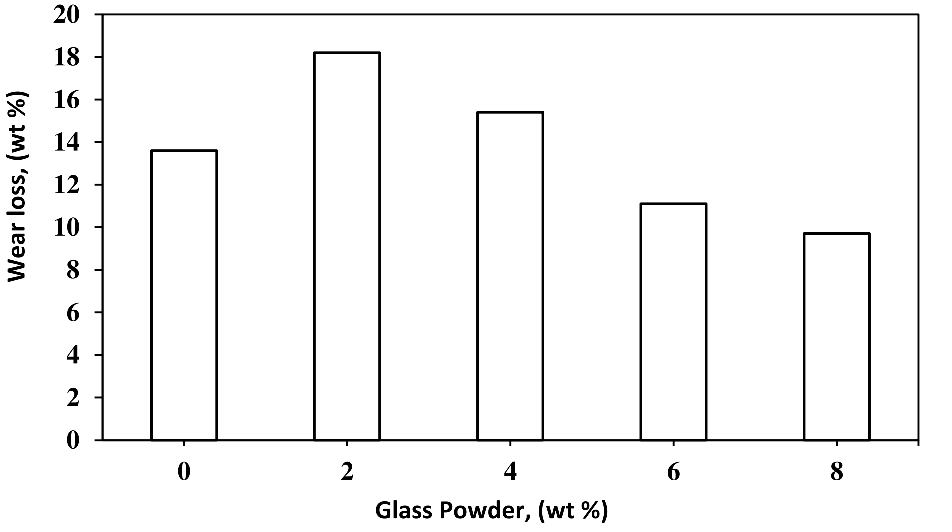

Fig. 9. Effect of glass powder content on the wear loss of the brake lining materials.

The wear losses of the brake lining samples are shown in Fig. 9. In this study, the wear loss of the base material was found to be 23.6 %. This value is lower than the mass loss of the 2 wt% and 4 wt% glass powder reinforced lining materials. This is because detached debris resulting from micro-cracks formed at a particular depth below the soft surface during sliding was smeared over the worn surface, owing to the effect of thermal and shearing stresses, as shown in Fig. 10a, Similarly, Yao et al. [14] reported that smear is the main characteristic of the mild wear zone. The wear losses of the 2 wt% and 4 wt% glass powder reinforced lining samples were higher than that of the base sample, as shown in Fig. 9. This was due to insufficient amounts of reinforcement material in the samples. After the soft elements of the brake lining materials were abraded during sliding, glass powder reinforcement elements were projected onto the friction surface.

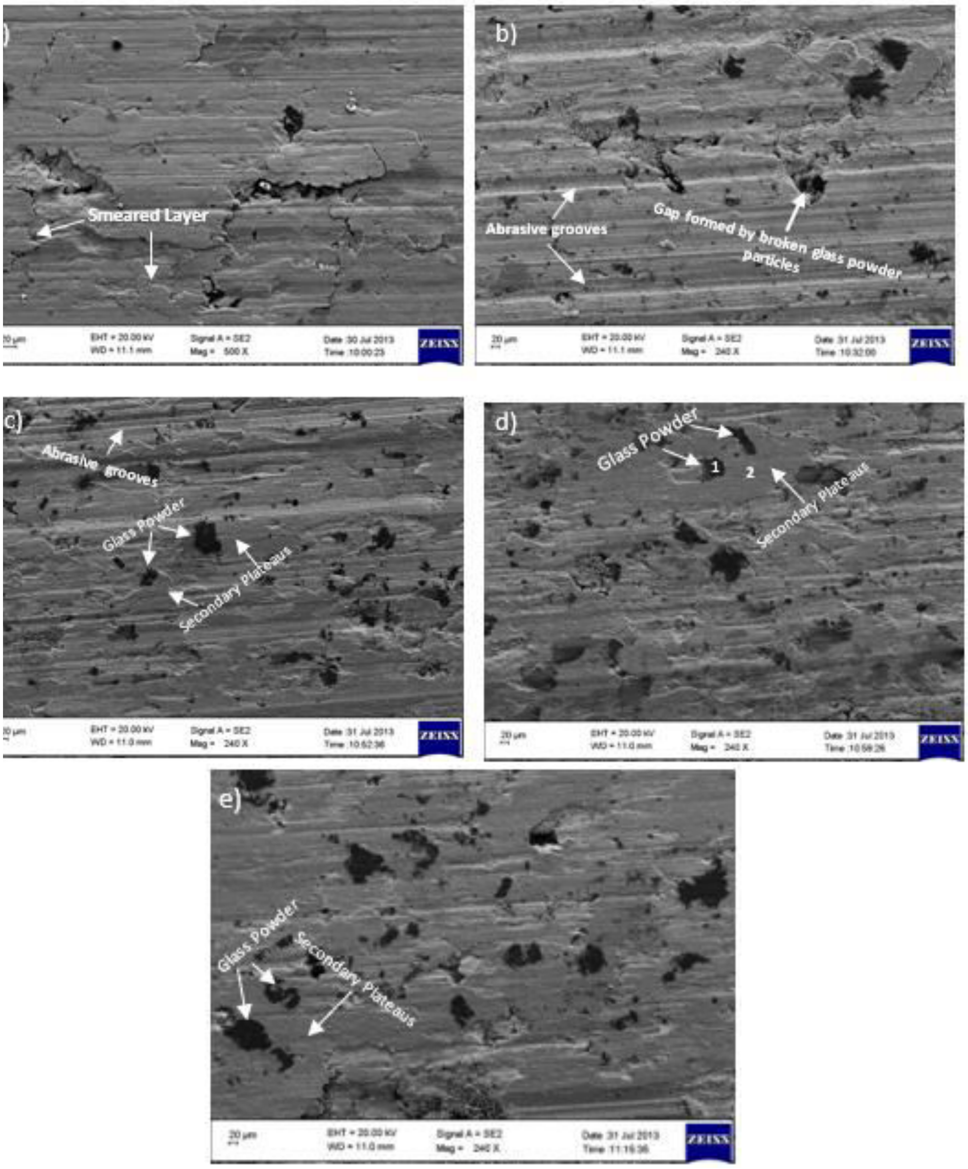

Fig. 10. SEM micrographs of the worn surfaces of the brake lining materials containing various amounts of glass powder: a) 0 wt% (500×); b) 2 wt% (240×); c) 4 wt% (240×); d) 6 wt% (240×); e) 8 wt% (240×).

The tangential force formed at the friction pair interface then caused the debonding of the glass powder by exceeding the shear-strength between the glass powder and matrix. As shown in Fig. 10b-c, the presence of these released particles led to micro-cutting abrasive wear. This is usually characterized by a high wear loss. Therefore, the wear loss of the 2 wt% and 4 wt% glass powder reinforced brake lining materials was higher than that of the unreinforced bronze-matrix material. With increasing glass powder ratios, the load-bearing area of the glass powder also increased, and so the pressure on the individual glass powder particles was accordingly reduced. Consequently, the potential for debonding during sliding was also reduced, resulting in a greater number of glass powder particles being present on the worn surface and a correspondingly increased tendency for the growth of secondary plateaus around glass powder particles through a process of agglomeration and compaction of the wear debris, as shown in Fig. 10c-e. The contact plateaus formed on the friction surfaces served as the main contact area while rubbing against the cast iron disc surface, and protected the brake lining materials from wear. Therefore, the wear loss of brake lining materials containing 4 wt%, 6 wt% and 8 wt% glass powder were lower than that of the 2 wt% glass powder sample. The findings of various researchers also showed that the presence of a stable friction film on the worn surface of brake lining materials leads to low wear loss [32].

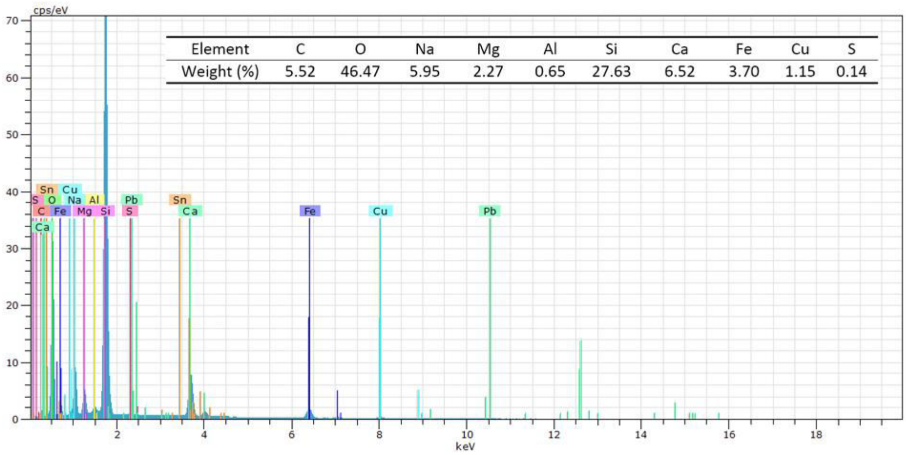

Fig. 11. EDS analysis results taken at position 1 on the 6 wt% glass powder reinforced brake lining sample surface in Fig. 10d.

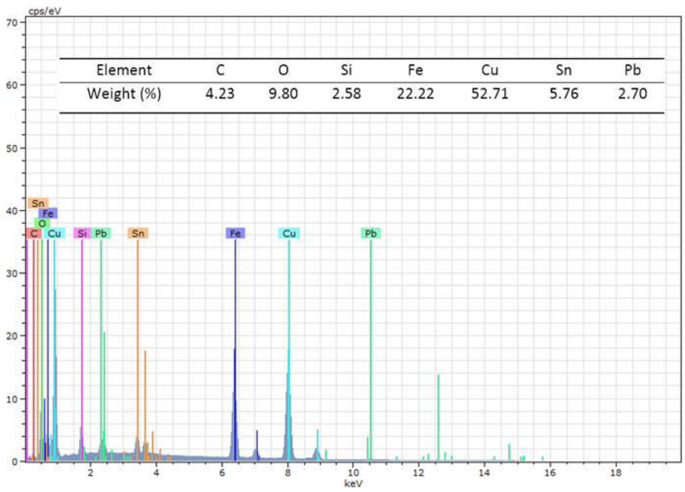

Fig. 12. EDS analysis results taken at position 2 on the 6 wt% glass powder reinforced brake lining sample surface in Fig. 10d.

The results of EDS analysis taken at positions 1 and 2 on the worn surface of the 6 wt% glass powder brake lining material shown in Fig. 10d are given in Figs 11 and 12. It was determined that position 1 consists of elements such as O, Si, Na, Ca, C, and Mg, as shown in Fig. 11. This result indicates that glass powder is present at this position on the surface. In addition, at position 2, elements such as Cu, Fe, O, C, Sn and Pb were detected, as shown by Fig. 12. The EDS analysis results clearly demonstrate that soft wear debris (Cu, Sn, Pb) formed secondary plateaus by a process of agglomeration around the primary plateaus (glass powder) during the wear test. An iron content of 22.22 wt% was also detected in the secondary plateaus. This indicates that the disc material (cast iron) was gradually transferred onto the worn surface of the friction materials during the sliding process, and that the disc material was exposed to low density abrasive wear by the brake lining material.

4. Conclusion

The tribological performances of brake friction materials containing various proportions of glass powder were investigated using a Chase-type friction tester machine, according to the SAE J661 standard. The following conclusions were drawn from these tribological tests:

1. The addition of glass powders to brake lining materials led to decreased density values in the samples, whereas their hardness values increased.
2. The highest friction coefficients were obtained for the brake lining material containing 6 wt% glass powder, and the brake lining sample containing 8 wt% glass powder exhibited the most stable frictional behavior.
3. The highest wear loss was exhibited by the 2 wt% glass powder brake lining material, an effect caused by debonding of the glass powder. The lowest wear loss was given by the 8 wt% glass powder reinforced brake lining material.
4. Adding waste glass powder to bronze-based brake lining materials improves their frictional and wear behavior without causing any noticeable increase in production costs.

Acknowledgments

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Сажетак: *У овом раду, материјали кочионих облога на бази бронзе са 0-8 wt% стакласног праха су добијени топлим пресовањем. Триболошка својства су испитивана фрикционим тестом типа Chase. Такође су одређени и густина и тврдоћа. Микроструктуре и фрикционе површи узорака су испитивани скенирајућом електронском микроскопијом. Као резултат, поврђено је да је узорак који је ојачан са 8 wt% стакластог праха показао најбоље понашање при хабању. Даље, примећена је редукција коефицијента фрикције у свим узорцима са повећањем температуре. Резултати су показали да стабилност коефицијента фрикције може бити повећана са порастом удела стакластог праха.*

Кључне речи*: материјали кочионих облога, стакласти прах, коефицијент фрикције, топло пресовање.*