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Original Research Article

Effects of fly ash introduction on friction and wear characteristics of brake pads

Ali Can Yilmaz[1, *]

Cukurova University, Adana Vocational School, Department of Motor Vehicles and Technologies, 01160, Adana, Turkey.

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* Corresponding author
acyilmaz@cu.edu.tr

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ABSTRACT

Fly ash is a waste matter generally emitted abundantly from chimneys of the production facilities and should mostly be recycled. In this context, this study reveals the tribological effects of fly ash on brake pad components by doping the fly ash in basic brake pad matrix with various weight fractions of 30% (S30), 35% (S35) and 40% (S40) by reducing aluminum powder in the pad matrix. According to the results, as the fly ash concentration increases in the matrix, density and hardness of the structure were prone to decrease to an extent. Water immersion technique was used to determine density values and specially modified pin-on-disc tribotester was utilized to measure coefficient of friction (CF) and specific wear rate (SWR) values between brake pad samples and the cast iron rotating disc. Among prepared samples, maximum average reduction in density and hardness were observed to be by 3.97% and 10.67%, respectively. S30 depicted the minimum CF of 0.32 and maximum CF of 0.43 was performed by S40. Maximum specific wear rate was observed for S40 subtending to an increase of 8.67% from that of S30 to S40. Results showed that, though higher escalation in CF as the fly ash fraction elevates in the matrix, wear rates did not show a dramatic increase which is an indication of effectiveness of fly ash in brake pads in terms of braking performance and long term durability.

Keywords: Fly ash, coefficient of friction, pin-on-disc tribotester, wear rate

1. Introduction

Brakes are indispensable components of transportation vehicles and their working principle is based on friction between brake shoe and brake disc (or drum) by converting kinetic energy to heat and rejecting it to the environment. As the automotive technology advances, there will always be more expectations from the brake system such as brake shoes with high resistance to overheating (less brake fade) and wear as well as having high friction coefficient values. On the other hand, brake shoes are to have a low friction coefficient to prevent wheel locking yet a high enough friction coefficient to give enough stopping power [1]. Thus, brake pads should be in composite structure consisting of several materials to conform to the demands. In general, these materials can be categorized into various groups: binder (generally phenolic resin) [2-5], fibers (minerals, metallic, ceramic, natural, synthetic) [6-11], fillers [12-15], friction modifiers [16-25] and metal powders [26-35].
Asbestos had been in use as filler material for several years due to its thermal stability up to

500 ºC, flexibility, low cost and fading resistance until it was banned considering health and environmental concerns [36, 37]. Several studies on fillers and abrasives different from asbestos have been conducted for brake pads [38-40]. Fly ash, as abrasive in brake pads, is one of the most pronounced among others since it is derived from the burning of pulverized coal and it flows through the chimneys of coal factories and trapped in specially designed particulate filters. Turkey's annual fly ash production is roughly 15 million tons and most of it becomes waste [41-43]. Fly ash composes of high hardness materials viz. silisium oxide and aluminum oxide with average particle size of 20 µm. Its thermal endurance is high as it is produced above 1000ºC and its high specific heat of 800 kJ/kg allows it to store heat energy released during braking. Low thermal conductivity of fly ash hinders transfer of stored heat to the brake metal and brake fluid, preventing failure of the brake system [32, 42, 44, 45].

Several studies have been conducted focusing on effect of dust fillers on friction and wear characteristics of the brake pads. Singh et.al. [46] fabricated cement kiln dust doped brake pads filled with different resins and analyzed their physical, mechanical and tribological properties. They concluded that the combination of cement kiln dust with phenolic resin exhibits the optimal results. An investigation on hardness and impact resistance of automotive brake pad composed with rice husk dust has been conducted by Bahari et.al. [47] and it was shown that hardness of the sample with rice husk dust is higher than that of the commercial brake pads. Handa and Kato [48] investigated the effects of Cu powder, $BaSO_4$ and cashew dust on tribological characteristics of automotive brake pads with varying the concentrations of the components and they compared the experimental results with multiple regression method. However, manufacturing method of a dust filler is of great importance in the context of braking performance and service life of the brake pads including hardness, density and surface roughness which directly affect the tribological behavior. In this study, a novel method of transfer molding was utilized in production of brake pad samples and relatively high density and hardness values were procured. To the author's knowledge, no study was performed using this production method. Furthermore, this study includes the examination of the effects of fly ash doping in three different concentrations on braking performance in terms of tribological behavior of brake pad-disc pair using a friction test bench. The coefficient of friction (CF) and specific wear rates (SWR) were considered as tribological performance parameters and compared for brake pad samples with various fly ash ingredients.

2. Experimental Details

2.1. Preparation of sample brake pads

The standard brake pad ingredients were purchased and used without any modification. Fly ash (Figure 1) concentrations were arranged to be 30 wt.% (S30), 35 wt.% (S35) and 40 wt.% (S40) in the phenolic based polymer matrix (mixture) by using high precision balance with sensitivity of $\pm 10^{-4}$ g. Resin based matrix was well blended (140 rpm) and transferred to the molding chamber via resin transfer molding (RTM) machine which is an effective technique in molding of resin based structures [49-52] as shown in Figure 2. Subsequent to blending of resin based matrix for 1 h, it was pumped by a specially designed high pressure RTM pump into the mold and compressed by the hydraulic pistons at pressure of 100 bar (10 MPa) and temperature of 150 ºC [46]. The phenolic resin fraction in the composition was deliberately kept a little bit higher than the average value (~16%) of currently used brake pads to facilitate the pumping process. Sand fraction in the matrix was also increased compared to average value to stimulate escalation in coefficient of friction between brake pads and brake disc. Both pressure and temperature values were determined via a data acquisition system directly connected to a custom software which receives data from a load cell (for pressure readings) and a temperature sensor. The final brake pad product was in 25 mm of diameter and 12 mm of thickness. At the end of the production process, the samples were placed in a furnace at 200ºC to remove any volatile contaminants and/or moisture from the structure which may negatively affect friction test results. Two identical samples for each fly ash doped brake pads (total of 6 samples for each experiment) were manufactured and assembled to the metal back-plates which were used as carriers. Composition of the final version of the samples is depicted in Table 1.

Table 1. Composition of the brake pad samples

Constituent (by wt.%)	S30	S35	S40
Phenolic resin	17	17	17
Graphite	8	8	8
Chalk	20	20	25
Sand	10	10	10
Aluminum powder	15	10	-
Fly ash	30	35	40

Figure 1. Fly ash used in the tests

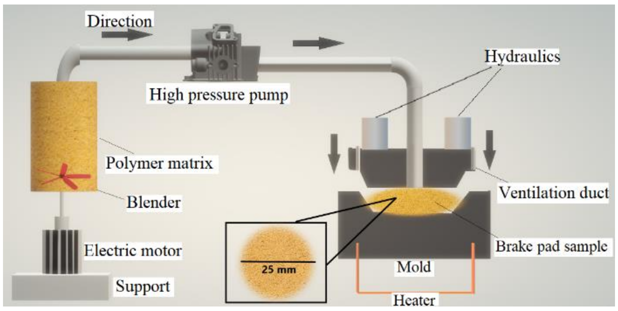

Figure 2. Illustration of sample preparation method

2.2. Hardness and density measurements

Hardness of the sample surface is an effective parameter that should be examined as durability and endurance against the wear process directly depend on it [53]. The samples underwent Rockwell hardness tests at 60 kgf load with steel ball indenter (12.6 mm diameter).

Density of the matrix is another characterization parameter since it directly defines the compressibility of the structure, that is, it manipulates the penetration of the indenter into the structure (hardness) [54, 55]. Nearly identical samples were deemed roughly in cylindrical shape and the specimens were precisely weighed before and after the fly ash doping process. Water immersion technique (Archimedes principle) was used to determine the density values.

2.3. Friction and wear analyses

The friction analysis was carried out on a modified pin-on-disc tribotester with an electric motor rotating the grey cast iron disc with hardness of 97.5 HRR. All friction and wear tests were done at sliding distance of 600 m subtending to 1000 revolutions of the disc. The pressure of the hydraulic unit was set to 30 bar corresponding to normal load of roughly 500 N exerted on the specimen to mimic mild average brake caliper clamping force. The hydraulic unit was installed to the system to imitate hydraulic braking system. The coefficient of friction was determined via a load unit connected to the data logger by taking the ratio of shear force between friction pairs to the normal load applied on the specimen and the disc. The illustration of the friction test rig is shown in Figure 3.

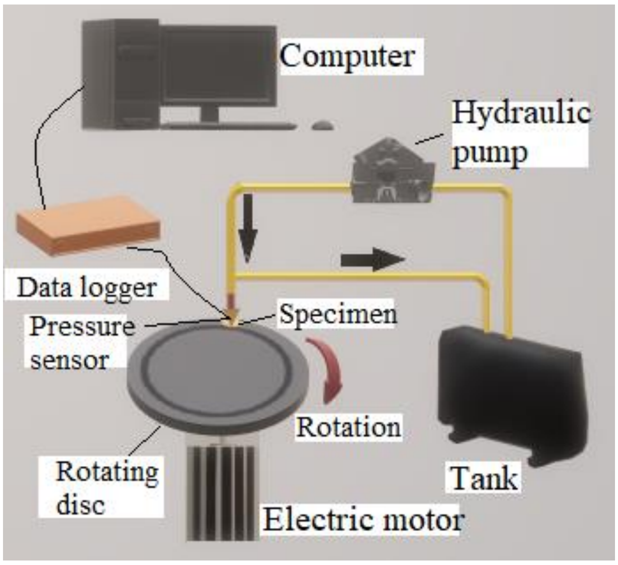

Figure 3. Schematic representation of the friction test rig

For each sample, wear analysis was performed considering mass loss by precisely weighing the samples before and after abrasion tests. The mass loss values are better converted to wear rates as it encompasses other tribological parameters as well as mass loss. One can calculate the specific wear rate as shown in Equation 1 [56]. All experiments were performed in triplicate and average values were taken into consideration to minimize data scattering.

$$SWR = \frac{\Delta m}{(2\pi D)(F_f N\rho)} \quad (1)$$

SWR: specific wear rate (cm^3/Nm)
Δm: mass loss of the specimen due to wear (g)
D: distance between centers of the disc and the specimen (m)
F_f: friction force (N), N: rotation of the disc (rev)
ρ: density of the specimen (g/cm^3)

3. Results and Discussion

3.1. Density and hardness measurements

The results of average hardness and density measurements of the samples doped with various amounts of fly ash are tabulated in Table 2. The theoretical calculation of the density values was performed using Equation 2 [57]. As the fly ash fraction increases in the matrix, the density of the samples tend to decrease. This can be attributed to the reduction of high density aluminum powder within the structure as the fly ash increases, previously as shown in Table 1. Substitution of low density fly ash with high density aluminum powder results in low density structure. Thus, the maximum reduction in density was 3.97% considering S30 and S40. On the other hand, the higher the density of the specimens, the more tightly packed the particles are, and hence offer more resistance to penetration and indentation, resulting in increased hardness. Therefore, the hardness of S30 was 10.67% higher than that of S40. The hardness increment yields lower contact area between friction pairs leading to lower wear rates [57, 29, 12].

$$\rho = \frac{X}{X-Y} \quad (2)$$

ρ: density of the sample (g/cm^3), X: dry weight (g), Y: wet weight (g)

Table 2. Average hardness and density values of the specimens

Parameter	S30	Sample S35	S40
Hardness (HRR)	114	108	103
Density (g/cm^3)	1.76	1.72	1.69

3.2. Coefficient of friction and wear rate measurements

Coefficient of friction (CF) strongly depends on the contact surface area of the substrates and the normal load exerted on the friction pairs. CF values are expected to be high to an extent for brake pads and S40 depicted the maximum average CF of 0.47 among others corresponding to a 34.36% improvement in CF considering S30 and S40. Increase in fly ash concentration yields higher active contact area between friction substrates, that is, higher friction forces and CF values. In general, CF is prone to depict a dramatic increase until the sliding distance of about 100 m for all samples. Considering average values, CF did not show a notable change especially for S30 as of sliding distance of 100 m. At the beginning of the friction tests, the sharp increase in CF may be attributed to the highest contact surface area between the specimen and the disc. As the specimen travels on the disc, number of contact regions starts to decrease to an extent (Figure 4).

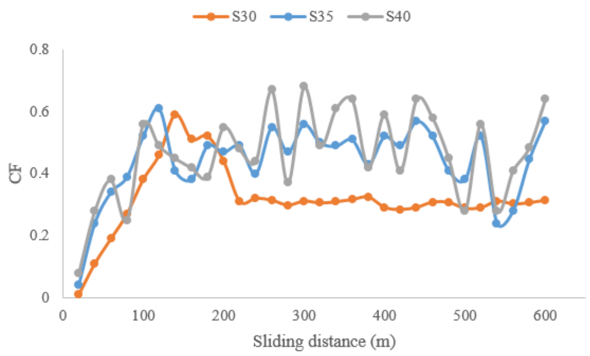

Figure 4. CF vs. sliding distance

Table 3. Average CF and SWR values

Parameter	S30	Sample S35	S40
Average CF	0.32	0.39	0.43
Average SWR (cm^3/Nm x10^{-6})	1.97	2.09	2.14

There was not a remarkable shift in wear rates of the specimens after the abrasion tests. S30 depicted the minimum wear rate, however, the results of S35 and S40 were not very distinctive from each other which is an important point for service life. This phenomenon may be due to higher hardness of S30 than the others. On the other hand, as the hardness of the specimens are not very far from each other, three specimens performed low wear rates. Nevertheless, high density of S30 leads to more closely packed particles which yields lower surface roughness and lower wear rates. A maximum increase of 8.63% in average SWR was observed from S30 to S40. Demonstration of the tribo-performance results of the samples is shown in Table 3.

4. Conclusions

This experimental study aims to make an investigation on tribological effectiveness of fly ash in standard brake pads. Considering that the fly ash is generally a waste and can abundantly be found due to its derivation from burning of coal, substituting this powder with aluminum powder in conventional brake pads would be prudent. Furthermore, results confirm that fly ash incorporation in brake pad matrix performs better results with regard to tribo-performance due its higher CF values which is a requested feature for a braking system. Though higher CF increment, significant change in wear rates was not observed between S30 and S40. Consequently, it can be said that fly ash is an appropriate doping matter for brake pad constituents in terms of lowering production costs, prolonging service life and protecting the environment as lower amount of fly ash will be released to the atmosphere.

Credit Authorship Contribution Statement

The author certifies that he has participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript.

Declaration of Competing Interest

The author declares no conflict of interest.

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