A Study on Development of Fly Ash Based Automotive Brake Lining

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Abstract—All over the world, Coal-fired power plants generate huge amounts of fly ash each year. Less than 40% of all fly ashes generated applications and rest have to be disposed off which is burden for the power generation industry. Fly ash particles possess certain characteristics that make them suitable for use in friction composites as a filler material. An attempt has been made through this research to incorporate more than 50% of fly ash particles in automotive brake lining friction composites. By this paper I present the research carried out on development of friction composites, using fly ash. Ingredients such as phenolic resin, aramid pulp, glass fiber, potassium titanate, graphite, aluminum fiber and copper powder were used in the composite development phase, in addition to the fly ash. The developed brake lining composites have exhibited consistent coefficients of friction in the range of 0.35–0.4 and wear rates lower than 12%. The developed compositions are 50–60% lighter than current commercial brake linings for similar friction, wear and temperature performance under dry and wet conditions. Fly ash particles were found thermally resilient enough not to decompose at typical braking temperature.

Keywords—Brake Lining; Fly Ash; Friction and wear; FAST-SEM Tests.

I. INTRODUCTION

Brake linings are the consumable surfaces in brake systems, such as drum brakes and disc brakes used in transport vehicles. Brake linings were invented by Bertha Benz (the wife of Karl Benz who invented the first patented automobile) during her historic first long distance car trip in the world in August 1888. Brake linings are composed of a relatively soft but tough and heat-resistant material with a high coefficient of dynamic friction (and ideally an identical coefficient of static friction) typically mounted to a solid metal backing using high-temperature adhesives or rivets. The complete assembly (including lining and backing) is then often called a brake pad or brake shoe. The dynamic friction coefficient "μ" for most standard brake pads is usually in the range of 0.35 to 0.42. This means that a force of 1000 N on the pad will give a resulting brake force close to 400 N.

Fig. 1. Brake lining pads
Since the lining is the portion of the braking system which converts the vehicle's kinetic energy into heat, the lining must be capable of surviving high temperatures without excessive wear (leading to frequent replacement) or out gassing (which causes brake fade, a decrease in the stopping power of the brake). Due to its efficacy, chrysotile asbestos was often a component in brake linings. However, studies such as a 1989 National Institutes of Health item showed an uncommonly high proportion of brake mechanics were afflicted with pleural and peritoneal mesothelioma, both of which are linked to chrysotile and asbestos exposure. Public health authorities generally recommend against inhaling brake dust, chrysotile has been banned in many developed countries, such as Australia in late 2003, and Chrysotile has been progressively replaced in most brake linings and pads by other fibers such as the synthetic aramids. [1] In the past, fly ash was generally released into the atmosphere, but pollution control equipment mandated in recent decades now required that it be captured prior to release. In the US, fly ash is generally stored at coal power plants or placed in landfills. About 43% is recycled, often used to supplement Portland cement in concrete production. Some have expressed health concerns about this.

![Fig.2 Fly ash particles at 2,000x magnification](image)

Fly ash is a fine, glass powder recovered from the gases of burning coal during the production of electricity. These micron-sized earth elements consist primarily of silica, alumina and iron. The difference between fly ash and portland cement becomes apparent under a microscope. Fly ash particles are almost totally spherical in shape, allowing them to flow and blend freely in mixtures. That capability is one of the properties making fly ash a desirable admixture for concrete.

1.1. Physical Characteristics of Fly ash:
- **Spherical shape:** Fly ash particles are almost totally spherical in shape, allowing them to flow and blend freely in mixtures.
- **Ball bearing effect:** The "ball-bearing" effect of fly ash particles creates a lubricating action when concrete is in its plastic state.
- **Higher Strength:** Fly ash continues to combine with free lime, increasing structural strength over time.
- **Reduced Sulfate Attack:** Fly ash ties up free lime that can combine with sulfate to create destructive expansion.
- **Reduced Efflorescence:** Fly ash chemically binds free lime and salts that can create efflorescence and dense concrete holds efflorescence producing compounds on the inside.
- **Reduced Shrinkage:** The largest contributor to drying shrinkage is water content. The lubricating action of fly ash reduces water content and drying shrinkage.

1.2 Types of Fly Ash:

1.2.1 **Class F fly ash**

The burning of harder, older anthracite and bituminous coal typically produces Class F fly ash. This fly ash is pozzolanic in nature, and contains less than 20% lime (CaO). Possessing pozzolanic properties, the glassy silica and alumina of Class F fly ash requires a cementing agent,
such as Portland cement, quicklime, or hydrated lime, with the presence of water in order to react and produce cementitious compounds. Alternatively the addition of a chemical activator such as sodium silicate (water glass) to a Class F ash can lead to the formation of a geopolymer.

1.2.2 Class C fly ash
Fly ash produced from the burning of younger lignite or subbituminous coal, in addition to having pozzolanic properties, also has some self-cementing properties. In the presence of water, Class C fly ash will harden and gain strength over time. Class C fly ash generally contains more than 20% lime (CaO). Unlike Class F, self-cementing Class C fly ash does not require an activator. Alkali and sulfate (SO₄) contents are generally higher in Class C fly ashes.

II. MATERIALS AND METHODS

2.1 Sample preparation
The development of formulations may be broadly divided into three distinct phases — were formulated based on the previous research experience. Compositions containing fly ash, phenolic resin, glass fiber and waste aluminum fibers were formulated and subjected to FAST procedure and full-scale automotive brake dynamometer testing. Inferences drawn from FAST results and surface characterizations using scanning electron microscope (SEM) were used to develop and/or modify the compositions further. The Phase-II compositions had glass fiber replaced with aramid pulp, as it was found that glass fiber could not provide enough thermo mechanical stability to brake lining matrix. Potassium titanate was also incorporating a friction modifier, since suggests that it works synergistically with aramid pulp to give an overall better friction performance for the brake pad lining. Graphite was also incorporated as a lubricant. The Phase-III or the most recent compositions were formulated to incorporate copper fiber/powder as a reinforcing agent in addition to all the previous ingredients that had been incorporated at the second stage.

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>Weight %</th>
</tr>
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<tbody>
<tr>
<td><strong>Phase I</strong></td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>55-65</td>
</tr>
<tr>
<td>Phenolic resin</td>
<td>20</td>
</tr>
<tr>
<td>Glass fiber</td>
<td>15-25</td>
</tr>
<tr>
<td>Aluminum fiber</td>
<td>0–10</td>
</tr>
<tr>
<td><strong>Phase II</strong></td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>52–60</td>
</tr>
<tr>
<td>Phenolic resin</td>
<td>20</td>
</tr>
<tr>
<td>Aramid pulp</td>
<td>3–8</td>
</tr>
<tr>
<td>Potassium titanate</td>
<td>4–10</td>
</tr>
<tr>
<td>Graphite</td>
<td>0–10</td>
</tr>
<tr>
<td><strong>Phase III</strong></td>
<td></td>
</tr>
<tr>
<td>Fly ash</td>
<td>50–60</td>
</tr>
<tr>
<td>Phenolic resin</td>
<td>20</td>
</tr>
<tr>
<td>Aramid pulp</td>
<td>3–8</td>
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<tr>
<td>Potassium titanate</td>
<td>4–10</td>
</tr>
<tr>
<td>Graphite</td>
<td>5–10</td>
</tr>
<tr>
<td>Copper fiber/powder</td>
<td>5–10</td>
</tr>
</tbody>
</table>

*Table No. 1 Development of fly ash-based automotive brake lining*

A specific amount of the mix was loaded into a cylindrical mold to fabricate FAST samples or full-scale brake samples, respectively. The mixes were pressed at a constant temperature of 180 C for 15
min. This process normally releases a lot of water from poly condensation process of phenolic resin. To eliminate cracking of the composite samples, pressure had to be released several times during the hot resing process. At the end of the hot-pressing process, samples were taken out of the mold, allowed to cool down to room temperature and were again cured at a constant temperature of 180°C for 4 h.

2.2 Testing of Composites:
Each composition was tested at least two times on the FAST machine to develop confidence in the data. The FAST machine uses a pearlite gray cast iron disc (diameter of 180 mm, thickness 38 mm) and a brake lining test sample with usual dimensions of 12.7 mm × 12.7 mm × 6.00 mm. In this research, larger, disc-size brake lining samples (2.5 cm diameter 6 mm) were used to increase the confidence levels. Each test sample was mounted on the load arm and pressed against the rotating disc. The rotating cast iron disc had a constant sliding speed of 7 m/s and the test duration was 90 min. The surfaces of the FAST samples and the cast iron discs had to be ground with 320-gritsandpaper before beginning the test. The normal load was varied to achieve a constant friction force. The friction coefficient was calculated by measuring normal and shear forces every 5 s over the entire duration of the test. The weight and thickness of the samples were noted before and after the friction test to calculate the total wear of each sample. An infrared sensor was used to record the temperature of the contact interface during the FAST and readings were recorded every second. In addition to the developed fly ash composites, an original equipment manufacturer’s (OEM) brake linings were purchased and samples cut out from it were subjected to FAST procedure. This composite did not contain any fly-ash and its test results served as the baseline.

The friction surfaces of the samples were characterized using SEM (Hitachi S2460N variable pressure). This electron microscope was supported with energy dispersive X-ray microanalysis (EDX) allowing chemical analysis. Representative samples were cut from the brake,

III. RESULTS

The fly ash particles undergo three distinct phase transitions, in terms of material loss and heat flow behavior, as the temperature is increased. The temperatures at which material transition/loss is initiated are known as onset temperature, and in case of this fly ash the three onset temperatures are 389, 632 and 823°C, respectively.

![Fig 3. TGA and DSC results of fly ash particles.](image-url)
The cumulative material loss up to the first transition is 1.76% and cumulative material loss up to the second transition phase is about 6.3%. But, typical automotive brake lining materials rarely experience temperatures larger than the first onset temperature, except for flash temperatures that may reach values of about 800°C. The material transitions observed are endothermic in nature and mostly reflect the physical transformations in terms of volatile matters escaping the bulk of the fly ash particles. As volatile materials present in fly ash are not expected to play a major role in the overall friction process, they may be suitable for being used as brake lining filler from a physico-thermal point of view.

Fig. 4. FAST results of OEM brake lining material.

Fig. 5. (a) & (b) FAST results of fly ash, phenolic resin, glass fiber and aluminum fibers composites.
The FAST results for the baseline OEM brake lining composite are presented in Fig. Each plot represents the time-dependent friction performance of a specific composition and the range of the ingredients in each composition is presented as inset in the respective figures. The low friction coefficient may be due to the entire absence of friction layer. Of the two compositions, the one having 55% fly ash provided a better performance and was selected as the composition for further modification. The total wear for both compositions was very high at around 56% by thickness and 52wt% at the end of 90 min FAST. Given the low coefficient of friction and high rate of wear, it was felt that the composite needed ingredient(s) to provide the necessary reinforcement to control wear as well as adhesion to generate higher coefficient of friction. Aluminum fibers were considered as a suitable component.

Aluminum fibers were chosen due to their availability as an industrial waste, lower specific gravity and relatively similar specific heat capacity as the fly ash. This is done to ensure a more homogeneous mix in terms of density and thermal properties. The oversized aluminum fibers were screened and only 1mm fraction was used for mix compositions. The aluminum fibers were added in 2, 5 and 10% in three different compositions. In all of the above compositions, amounts of fly ash were varied while increasing/decreasing the aluminum fiber content.

The FAST results for the above compositions are shown in Fig.6. The 2% addition of aluminum fibers did not significantly improve the friction behavior, when compared to the no aluminum samples. There were initial variable peaks followed by drop in the friction coefficient. However, the 5% aluminum composition exhibited a consistent behavior, with the coefficient friction of about 0.22. The 10% aluminum composition exhibited a higher coefficient of friction for about 60 min of the test duration before dropping down sharply to around 0.2. The FAST samples with 2% aluminum had a total wear of 41.8% by thickness. The 5% aluminum composition showed a total wear of 38.6% by thickness. The 10% aluminum composition showed a total wear of 40.5% by thickness and 41.5%.

Surface characterization of the above FAST samples revealed that soft aluminum fibers in the composites were plastically deformed and smeared over the contact surface generating excessive...
adhesion. Aluminum fibers pulling out due to excessive adhesion may cause over torques in such compositions. It was also noted from the SEM images that a glassy phase was formed over the areas of contact (i.e. the aluminum fibers). High total wear >35% of the samples pointed out the inability of the glass fibers to provide adequate reinforcement to generate a coherent matrix to the fly ash particles. To overcome this behavior of glass fiber, aramid pulp was considered as a replacement and was used in conjunction with potassium titanate. Graphite was also added to overcome any excessive adhesion and generate a more stable friction performance.

During Phase II, the initial compositions were formulated adding only aramid pulp and potassium titanate to fly-ash and resin. The FAST results for two such compositions are presented in Fig. both the compositions exhibited a coefficient of friction in the range of 0.2–0.3 and the frictional behavior was much more consistent than in the case of samples with glass fibers. The total wear rates ranged between 12% and 14% for both the compositions, with respect to thickness and weight, respectively. These wear rates were substantially less than the formulations with glass fiber. As a follow-up step, graphite was added to the mix and new compositions were subjected to FAST. The FAST results of two compositions containing graphite in addition to ash, resin, aramid pulp and potassium titanate are presented in this. Also, presented in the figure are the ranges of each ingredient.

Both the samples exhibited very stable FAST behavior and coefficient of friction averaged about 0.4. The total wear for these two samples were in the 14–17% range, with respect to both thickness and weight. These were significant improvements as compared to previous samples. The above two composition samples were analyzed under the SEM. The bulk structure was observed to be very
homogeneous and compact, which could be attributed to the combination of aramid pulp and potassium titanate. This may have led to lesser total wear in the FAST samples. Friction layer was also seen to have developed all over the contact surface, which may be attributed to the presence of graphite. The friction layer in turn hosted the abrasives present in the fly ash that may have contributed to the larger values of coefficient of friction. Hence, the need for an ingredient that could scrape off the excess friction layer and generate a higher coefficient of friction was felt at this stage. Copper was chosen because of its previous proven impact on stability of coefficient of friction. The bulk density of all the fly ash composites was determined to be in the range of 1.5–1.75 g/cm³. This is about 60% lighter than a typical commercial brake lining. The most recent composite samples (Phase III) were fabricated using fly ash, resin, aramid pulp, potassium titanate, graphite and copper fibers/powder.

![Graph](image)

**Fig.8. FAST results of fly ash, phenolic resin, aramid pulp, potassium titanate, graphite and copper fiber/powder composites.**

The amount of copper was minimized to limit the diversity between fly-ash and copper fiber/powder in the composite matrix. Also, for the same reason copper powder was used in certain compositions to limit the disparity in particle size between copper powder and fly ash. The FAST results of three such compositions are presented in Fig. The coefficient of friction detected in FAST was consistently around 0.4. The total wear was also very low as well in case of both the compositions (5–9%). At this stage, it is believed that copper fibers or powder are providing a stable friction layer containing copper oxides, while at the same time acting as a reinforcing agent. Composite samples containing copper powder produced a more consistent friction in FAST than samples containing copper fibers.

Surface analysis of the above samples revealed uniform and consistent wear and generation of friction layer uniformly distributed over the entire contact surface. This could explain the stable coefficient of friction values and the low wear rate. For all the compositions tested on the FAST, temperatures developed at the contact interface were recorded using an infrared sensor. The sensor picks up reading only when the temperature of the body being monitored exceeds 50 C. Comparative data collected for one of the fly ash composites containing copper fibers and the OEM brake lining composite (baseline sample) are presented in Fig. Both the fly ash and baseline sample witness similar temperature rise behavior.

The maximum temperature reached by fly ash composite is slightly more than that of the baseline composite, which could be attributed to lower thermal conductivity of the fly ash. The sudden drop
in interface temperature at the end of FAST test for the fly-ash composite may be explained as follows.

FIG. 9. SEM micrographs of fly ash composite containing copper powder.

FIG. 11. Temperature at the friction interface as a function of time during FAST.

The high specific heat of large volume of fly ash particles combined with the low thermal conductivity may have prevented the bulk temperature of the fly ash composite from rising, while only raising the outer interface temperature. This may have led to the sudden temperature drop at the end of the test.

IV. CONCLUSION

- The developed compositions are 50–60% lighter than current commercial brake linings for similar friction, wear and temperature performance under dry and wet conditions. Fly ash particles were found thermally resilient enough not to decompose at typical braking temperature.
- Composite samples that contained glass fiber, aluminum fiber could not provide desirable coefficients of friction and wear rates.
- Aramide pulp and potassium titanate provided sufficient structural reinforcement to the composite matrix that contained large percentage of fly ash particles.
• Addition of graphite helped the fly ash composite samples maintain stable friction performance. But, a metallic constituent in the form of copper fiber/powder was needed to scrape off excess lubricating layer generated by graphite. For similar compositions, FAST samples containing copper powder exhibited fewer vibrations than those containing copper fiber.

• The contact interface temperature monitoring of Phase-III FAST samples indicated similar behavior, as that exhibited by optimized commercial brake lining samples. The recent most brake lining compositions containing copper fiber/powder have shown encouraging results for further testing and optimization.

REFERENCES


