Influence of Alumina Fiber Content on Properties of Non-Asbestos Organic Brake Friction Material

RAHUL P. TALEGAONKAR AND K. GOPINATH*
Machine Design Section, Department of Mechanical Engineering
Indian Institute of Technology Madras, Chennai 600 036, India

ABSTRACT: In order to replace the conventional asbestos friction material, a non-asbestos organic (NAO) friction material is developed with alumina fiber. The effect of alumina fiber content from 0–20 wt% on the physical and mechanical properties is investigated. Making use of these properties, the wear properties are predicted. It is observed that with the increase in alumina content the specific gravity and the elastic modulus of the material decreases. But the compressive strength, hardness, tensile strength, and shear strength increases linearly. There was no significant change in glass transition and decomposition temperature of the composites with variation in alumina fiber content. The theoretical prediction based on simplified assumptions indicates that wear properties are improving with alumina content.

KEY WORDS: alumina fiber, brake friction material, specific gravity, mechanical properties, thermal analysis.

INTRODUCTION

THE BEGINNING OF the twentieth century started with marked usage of asbestos fiber in friction material [1,2]. This was because asbestos was imparting good compression strength, high thermal and corrosion resistance, high friction and wear resistance, and good compatibility with cast iron and steel mating disc materials. It was amenable to easy formulation with polymer binder and molding. Above all it was economical and met the majority of desirable properties of brake friction material. It was hailed as the 'wonder fiber' for friction materials attracting widespread use of asbestos.

After considerable usage and experience with the material, in 1950, the carcinogenic effect of asbestos dust inhalation on human beings was revealed. In 1972, the Occupational Safety and Health Administration (OSHA) issued guidelines for air-borne asbestos and in 1987, the Environmental Protection Agency (EPA) included it in the list of hazardous materials [2–4]. A subsequent ban on asbestos forced rapid development of NAO friction material and its commercial usage in developed countries. Developing countries are also following the same path and slowly phasing out the asbestos friction material.

The composition of the commercial NAO friction material is kept as a trade secret. However, some of the publications available show that asbestos has been replaced with glass, aramid, carbon and ceramic fibers, steel, and rock wool. Besides these, a few more

*Author to whom correspondence should be addressed. E-mail: gopinath@iitm.ac.in

0731-6844/09/17 2069–13 $10.00/0 DOI: 10.1177/0731684408091684

Los Angeles, London, New Delhi and Singapore

ingredients are added to compensate for the properties of asbestos. The brake material survey indicates that various ingredients used are the resin 15–20%, fiber 30–40%, filler 10–20%, friction dust 10–20%, and materials for special effects 5–10% by weight [1,3,5]. When alumina particles are used in polymer-based model composites, Durand et al. [6] found a significant improvement in wear resistance. Further it also improved the thermal stability of the material. The epoxy bonded friction materials they developed had a hardness of 10 to 50 HV_1.

Eriksson et al. [7] in their study on tribological surfaces used a brake pad with 30 wt% fiber to achieve good strength, friction modifier up to 38 wt% to stabilize the friction, 5 wt% friction additives to improve friction, 11 wt% rubber chips to improve the damping, and 8 wt% resin to bond the ingredients. For the braking pressure of 1.5 MPa and sliding speed of 0–3 m/s of the rotor disc, friction was in the range 0.5–0.6. Osterle et al. [8] used a brake pad with 2 wt% organic fibers, 48 wt% metals, 22 wt% fillers, 10 wt% lubricant, 12 wt% rubber chips and 6 wt% resin. For brake operating pressure of 0.5 MPa and sliding speed of 9.2 m/s, they obtained friction in the range 0.3–0.4. Gopal et al. [9] used up to 20 wt% barite, 40 wt% fiber, 40 wt% resin and varied the Kevlar fiber content from 0–12 wt% by replacing barite correspondingly. For a sliding speed 5.8–11.2 m/s and pressure 0.69 MPa, friction range was 0.25–0.4.

From the survey of materials, it is observed that the alumina fiber in the place of alumina particulate is likely to impart better strength to the friction material. It also has good thermal stability and is non-toxic. Since the information on the use of alumina fiber for friction material is scarcely available, it is a worthwhile proposition to investigate it. Hence, for the current study, the influence of alumina fiber content from 0–20 wt% on physical and mechanical properties of NAO friction material is explored. From these properties, an attempt is made to predict the wear behavior.

MATERIALS AND METHODS

A majority of friction materials for passenger car brakes in use have a coefficient of friction in the range 0.3–0.4 while operating up to a pressure (P) of 1.5 MPa, speeds (V) up to 9 m/s, and PV (product of P and V) up to 8 MPa m/s. The densities were between 2.0 and 4.0 g/cc and a hardness value of about 50 HV_1 [1,5–9]. This information serves as a guideline for the development of new NAO friction material.

Material Development

As a trial, a base composition was evolved with 20 wt% steel wool which can impart good thermal conductivity and strength, 5 wt% each of glass and rock wool to further improve the strength, 5 wt% of graphite to obliterate any seizing tendency of the steel wool at the friction surface and improve smooth operation, 10 wt% of friction dust to stabilize the friction, 25 wt% barite and 5 wt% chalk powder as filler materials, and 25 wt% of phenolic resin as bonding material. The friction material developed satisfied the requisite strength properties. Hence for the study, alumina fiber was added to the base composition in steps of 5 wt% up to 20 wt% and correspondingly the barite content was reduced in the base composition. The details of the five grades of NAO friction material developed are given in Table 1.

In order to obtain a homogeneous mix, a sequential mixing procedure derived from earlier experience was adopted. First, the alumina fibers and the rockwool were churned

together for 6 min in a drum mixer. The feeder and chopper were both switched on at 120 rpm. Then straight phenolic resin was added and the mixer was run for 5 min. Steel wool, barite, graphite, and chalk powder were added and mixed for the next 15 min. Finally, glass fiber was added and the mixer was run for 4 min. This time the chopper was turned off in order to prevent damage to the glass fibers. This was followed by the molding cycle.

The brake friction composites in the form of slabs were molded in an hydraulic press (Glasnost Hydraulics) of 150 ton capacity. A mix weight of 1.5 kg was taken into a die for compaction. The top and bottom temperature of the die was maintained between 130 and 150°C. A compaction pressure of 17–21 MPa was maintained. The press curing cycle was maintained for 8 min. Five breathing cycles were followed by final curing. The breathing cycles helped to remove entrapped gases evolved during cross-linking reaction of the resin. Details of the molding cycle are shown in Figure 1. The fabricated composites were cut into the required specimen size for various tests.

Table 1. Composition of non-asbestos organic friction material samples.

Ingredient	Content in wt%				
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Alumina fiber	0	5	10	15	20
Glass fiber	5	5	5	5	5
Rockwool	5	5	5	5	5
Steel wool	20	20	20	20	20
Phenolic resin	25	25	25	25	25
Barite	25	20	15	10	5
Graphite	5	5	5	5	5
Chalk powder ($CaCO_3$)	5	5	5	5	5
Friction dust	10	10	10	10	10

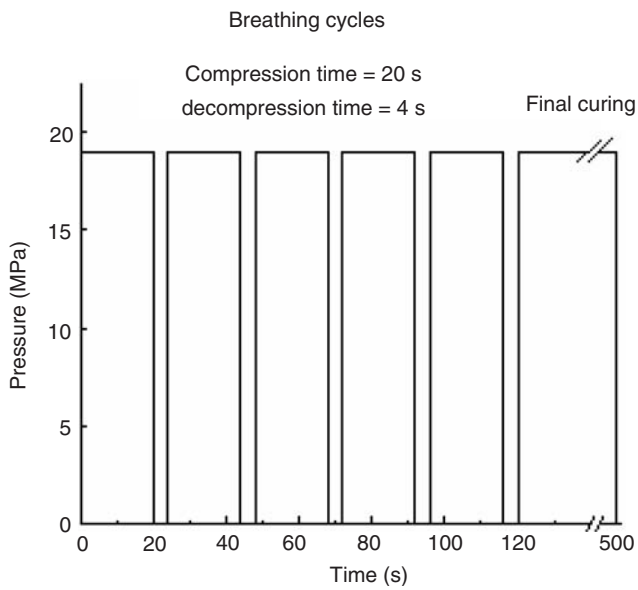

Figure 1. *Molding cycle for the composites.*

RESULTS AND DISCUSSION

Property Evaluation

PHYSICAL PROPERTY

The specific gravity of the friction materials was measured as per the specifications given in SAE J 380 SEP 93 standard [10]. A Mettler PM 400 weighing balance with density determination kit was used. For each composite, 10 samples were used and the specific gravity was calculated using:

$$S = \frac{W_a}{W_a - W_w} \tag{1}$$

where S is the specific gravity, W_a is the weight in air, and W_w is the weight in water. The average specific gravity for the composites is shown in Figure 2.

It is noted in Figure 1 that the specific gravity of the material decreased linearly with increase in alumina content. This is obvious as the alumina fiber is replacing heavier barite. The decrease in the specific gravity is advantageous for brakes as it reduces the un-sprung mass of the vehicle. The relation between specific gravity (S) and alumina fiber content (x) is given as:

$$S = -0.0035x + 2.1718. \tag{2}$$

The specific gravity of friction materials developed for the study lies within the range mentioned in the guidelines.

THERMAL ANALYSIS

In the working of brakes, friction materials are subjected to high temperatures due to friction. If temperature reached is high enough, it results in softening or sometimes even in

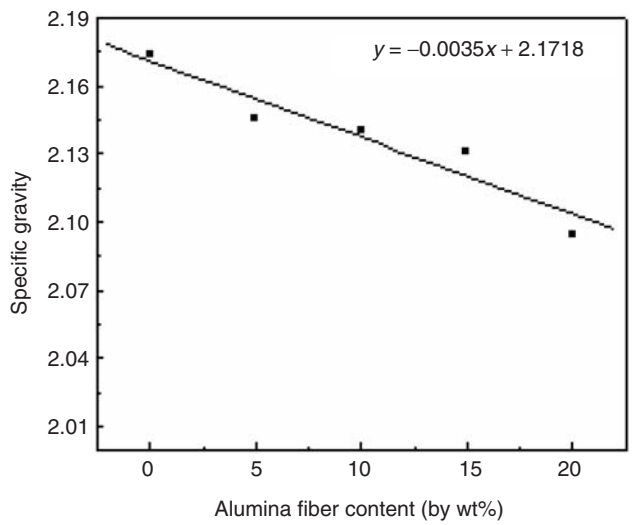

Figure 2. *Variation of specific gravity with alumina fiber content in friction materials.*

decomposition of the friction materials. To know about thermal behavior of the friction materials, differential scanning calorimetry (DSC) and thermo-gravimetric analysis (TGA) was carried out.

At higher temperatures, the polymer matrix becomes soft and hence shear strength of the composites reduces. The temperature at which polymer matrix changes from a glassy state to a rubbery state is called the glass transition temperature (T_g). To know T_g of the five friction materials, DSC evaluation was carried out in a NETZSCH DSC 204. A typical DSC thermogram for the friction material with 10% alumina fiber content is shown in Figure 3.

The variation of T_g with alumina content is shown in Figure 4. It was observed that T_g for other composites was also around 250°C. There was no significant change in T_g

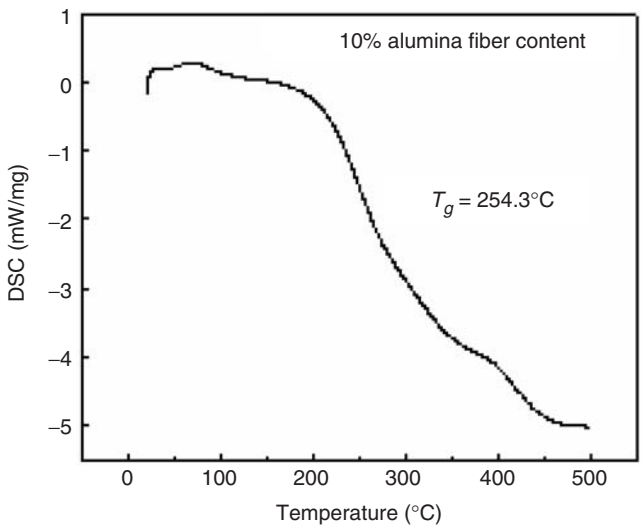

Figure 3. *DSC thermogram for brake friction composites with 10% alumina fiber content.*

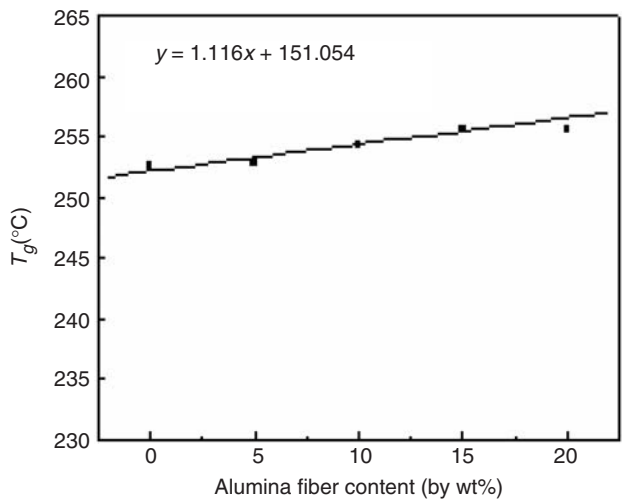

Figure 4. *Influence of alumina content on glass transition temperature of the NAO friction materials.*

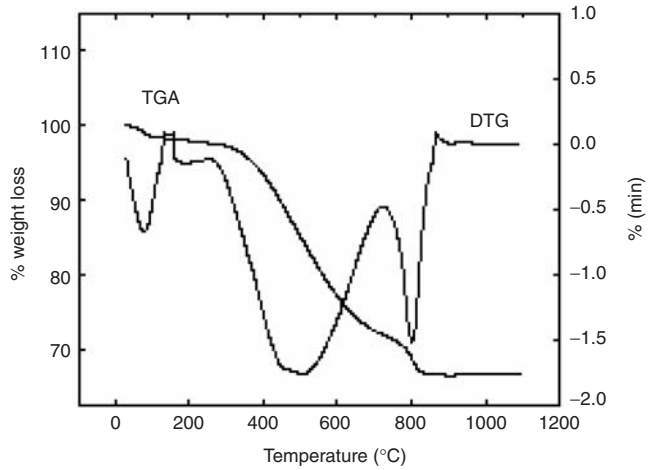

Figure 5. *TGA and DTG thermograms for composite with 10% alumina fiber content.*

with increase in alumina fiber content in the friction composites. T_g is a property of phenolic resin and hence it is noted that the effect of alumina fiber content on T_g is not significant.

Alumina fiber has high temperature stability. So, to know if different contents of alumina fiber have any influence on decomposition of composites, TGA was carried out. The TGA and differential thermal gravimetry (DTG) thermogram for friction material with 10% alumina fiber content is given in Figure 5. From the TGA curve, it is clear that decomposition takes place at around 300°C. Similar results were also obtained for the other friction materials. Hence, it is clear that alumina fiber does not have any significant influence on the decomposition temperature of the friction materials. The decomposition of the friction composites was due to decomposition of phenolic resin.

Mechanical Properties

During application of brakes, a compressive force acts on the friction composites. The composites should have high compressive strength and should not fail under the applied braking pressure. To know about compressive strength of these composites, tests were carried out using Instron 3367 using 10 mm cubic specimens. Three samples of each composite were tested and the average value was calculated. Compressive stress–strain behavior of a specimen with 10% alumina fiber content is shown in Figure 6. The maximum compressive strength was 138.70 MPa while breaking stress was 34.9 MPa. The compression at break point was 1.1193 mm (14.57%). Linear stress–strain behavior is exhibited until the ultimate point of the curve.

Compression test results for the friction composites are shown in Figure 7. Maximum compressive strength and strain are plotted against the alumina fiber content in friction composites. The relation between compressive strength (σ_c) and alumina fiber content (x) is given as:

$$\sigma_c = 13.657x + 99.719. \tag{3}$$

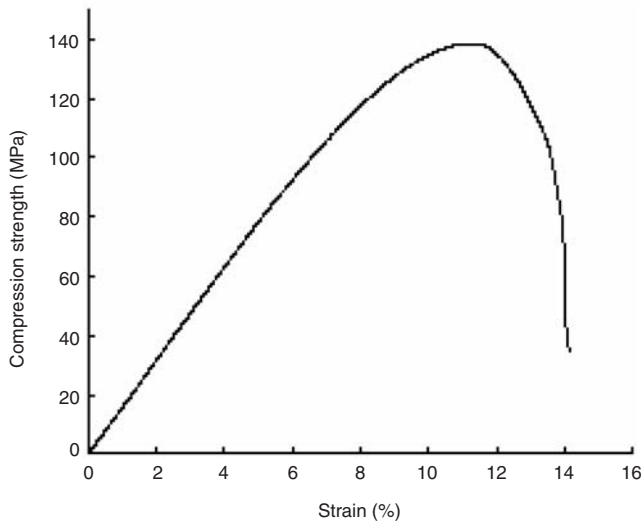

Figure 6. *Compression test result for the composite with 10% alumina fiber content.*

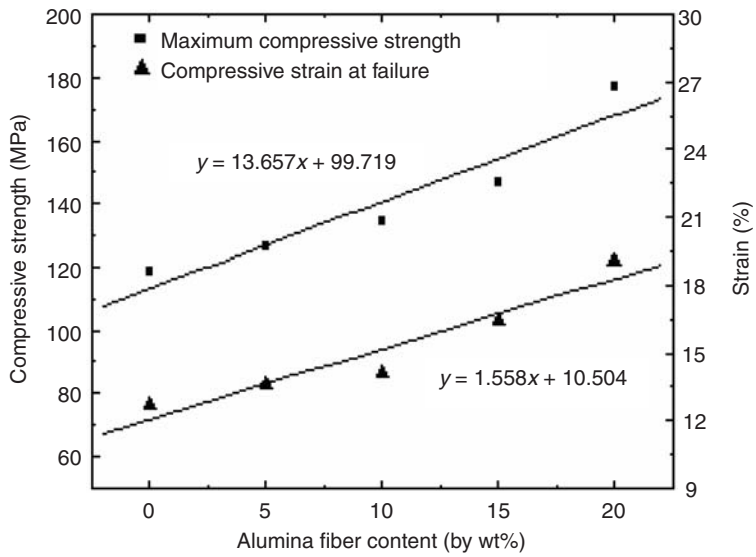

Figure 7. *Compression test result for friction composites.*

Figure 7 shows that compressive strength as well as the strain increases with an increase in the alumina fiber content in friction material. This is because of the reinforcing effect of the fiber. The combined effect is an increase in the toughness of the material. The compressive strength of a commercial friction material evaluated gave a value of 110 MPa. The current NAO developed had a strength better than the above and was in the range 120–170 MPa.

Hardness of the composites was measured by the Shore D scale. For each composite, hardness was measured at ten different locations and average hardness was taken

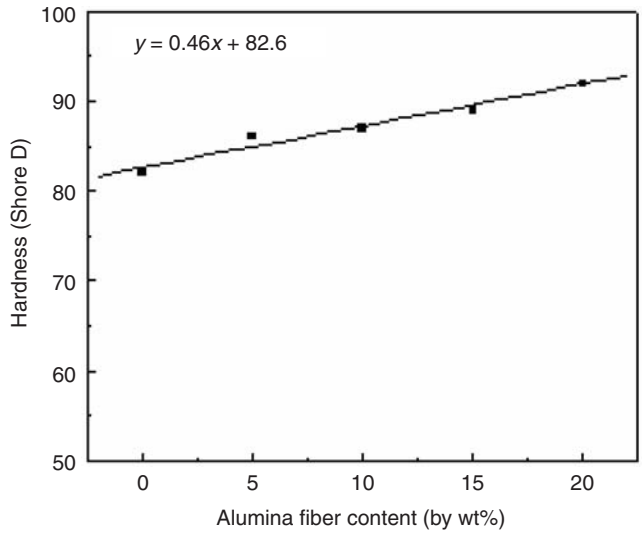

Figure 8. *Variation of hardness with alumina fiber content in friction materials.*

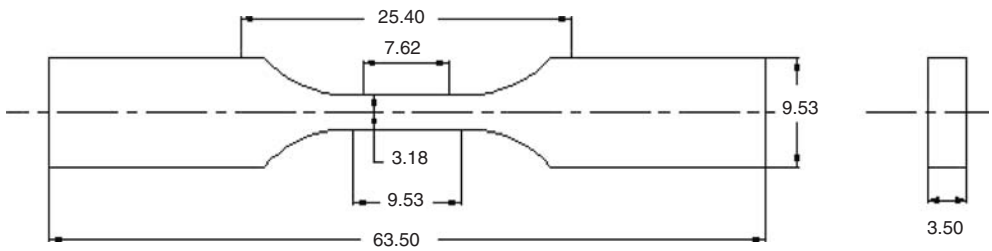

Figure 9. *Specimen dimensions for the tensile testing.*

for representation. Variation of hardness with alumina fiber content in the friction composites is shown in Figure 8.

The relation between hardness (H) and alumina fiber content (x) is given by:

$$H = 0.46x + 82.6. \tag{4}$$

The linear increase in hardness with alumina content is expected since it is the hardest component among the ingredients in the material. Its increase is hence bound to increase the hardness.

The tensile testing was carried out according to ASTM D 638-1 [11]. Five specimens of each composite were tested and average ultimate tensile strength was calculated. The standard specimen dimensions in mm are given in Figure 9. The specimens were tested on a Universal Testing Machine (UTM). A stress–strain diagram for a specimen with 10% alumina fiber content is shown in Figure 10. The material shows elastic limit up to a stress of about 7 MPa. The ultimate tensile strength was 28.07 MPa. The total elongation was 1.035 mm (1.63%). There was no yielding in the material. This behavior is near to that of a brittle material.

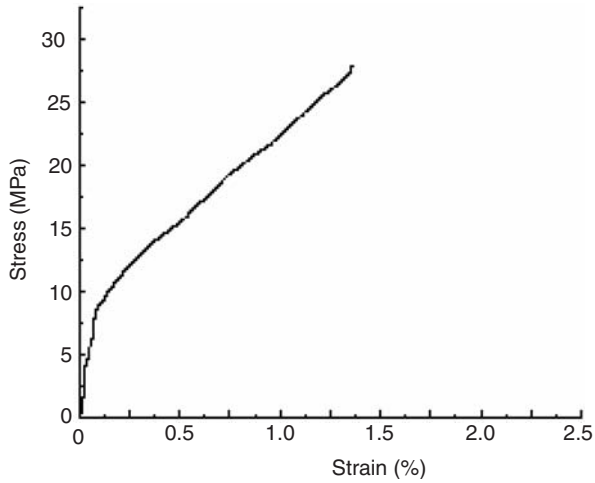

Figure 10. *Tensile test result for the composite with 10% alumina fiber content.*

Table 2. Tensile test results for friction materials.

	Up to elastic limit				
Al_2O_3 content (wt%)	σ_t (MPa)	ε (%)	*E* (GPa)	σ_{ut} (MPa)	ε at failure (%)
0	7.02	0.032	21.938	30.414	1.28
5	7.25	0.046	15.760	32.65	1.43
10	7.47	0.081	9.222	33.42	1.57
15	7.54	0.088	8.568	36.28	1.78
20	8.11	0.114	7.114	37.291	1.85

The tensile strength results for the friction composites are shown in Table 2. The ultimate tensile strength deviation for the composites is shown in Figure 11. The relation between ultimate tensile strength (σ_{ut}) and alumina fiber content (x) is given by:

$$\sigma_{ut} = 0.3477x + 30.534. \tag{5}$$

The tensile strength increased with increase in the alumina fiber content owing to the reinforcing effect of alumina fiber in the composite.

Tensile strength of composites with various fibers, in a study of fade and recovery behavior investigation by Bijwe and Satpathy [12], was in the range 6.4–17.7 MPa. The values obtained in the present study are higher which indicate better strength of the composites.

The shear strength of the composites was measured following ASTM D 732-99 standard [13]. In this case, a punch tool is used to shear the specimen. The specimen geometry (in mm) used here is shown in Figure 12. The testing is carried out on a UTM. Five specimens of each composite were tested and average ultimate shear strength was calculated. The shear strength for the friction material is shown in Figure 13. Variation of shear strength (τ) with alumina fiber content (x) is given as:

$$\tau = 0.4848x + 22.327. \tag{6}$$

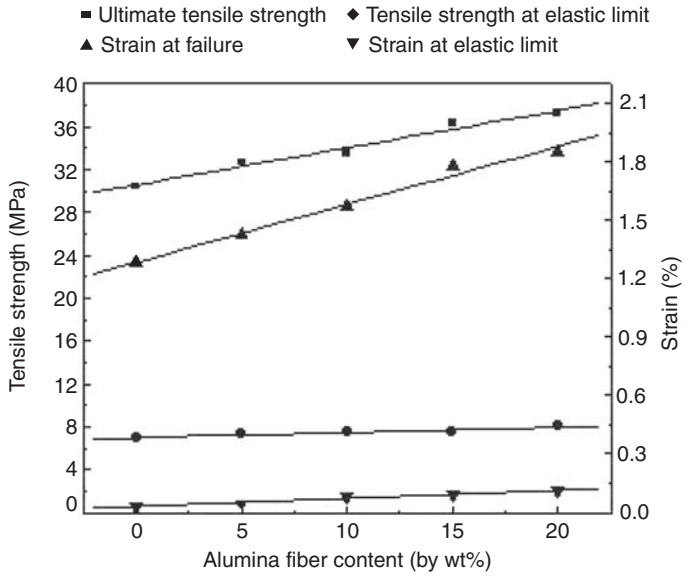

Figure 11. *Tensile strength and strain of the friction composites.*

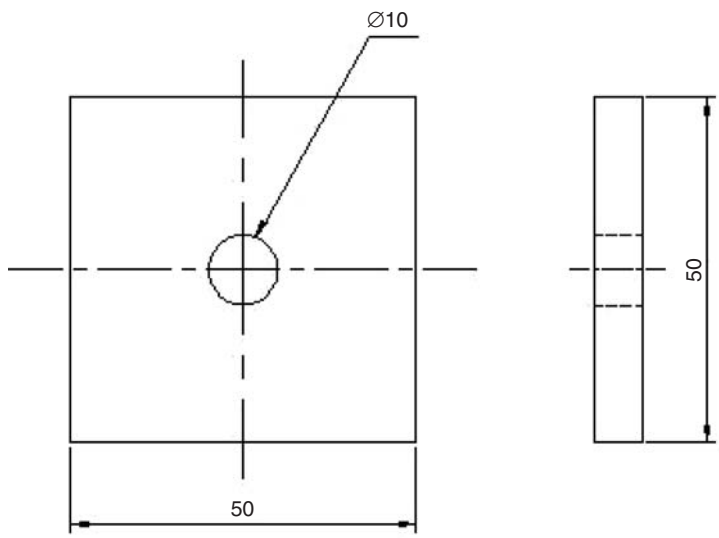

Figure 12. *Specimen dimensions for shear testing.*

Shear strength increases with increase in the alumina fiber content. The presence of fiber in the resin matrix increases its shear resistance. Hence with increase in the alumina fiber content, the number of fibers increases, and the shear strength of the composite.

Prediction of Wear Resistance

In the case of polymer matrix composites such as friction materials, adhesion and abrasion are the two dominating wear mechanisms. Using the mechanical properties

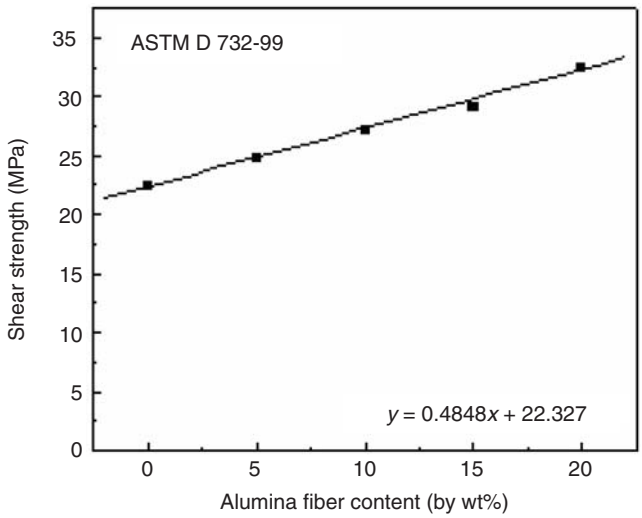

Figure 13. *Shear strength of the friction composites.*

obtained in this study, an attempt is made to predict adhesive and abrasive wear resistance of the friction composites. Wear performance is predicted using relative wear resistance which is defined as 'ratio of wear of composite with 0% alumina fiber content to wear of a composite'. In mathematical form:

$$\text{relative wear resistance} = \frac{\text{wear of composite with 0\% alumina fiber content}}{\text{wear of the composite}}. \quad (7)$$

The friction composite with 0% alumina fiber content is a base composite and hence it is used for comparison.

In the case of adhesive wear, Burwell's equation [14] is used for calculation of wear volume (V). It is given as:

$$V = \frac{KWL}{H} \quad (8)$$

where K is the wear coefficient, W is the normal load applied, L is the total sliding distance, and H is the hardness. Thus wear is inversely proportional to hardness of the composite. In other words, wear resistance is directly proportional to hardness. For a particular load and sliding distance, relative wear resistance is measured as given by:

$$\text{relative adhesive wear resistance} = \frac{\text{hardness of a composite}}{\text{hardness of base composite}}. \quad (9)$$

The relative wear resistance in adhesion for the composites is shown in Figure 14. Wear resistance is the maximum for friction composite with 20% alumina fiber content and it is 1.07 times that of base composite. This is because of high hardness of this composite, as it contains maximum amount of alumina fiber.

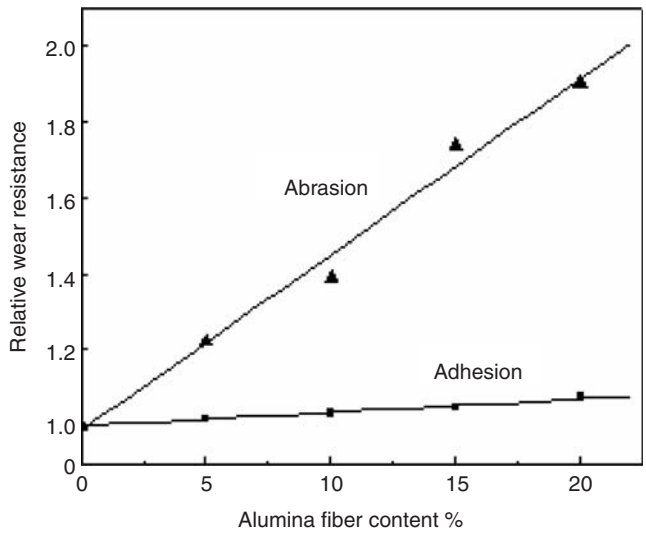

Figure 14. *Relative wear resistance of the friction composites in adhesion and abrasion.*

In the case of abrasive wear, Ratner's relation [15,16] is used to give wear volume (V). It is given as:

$$V = \frac{K\mu WL}{H\sigma_{ut}\varepsilon}. \tag{10}$$

where K is proportionality constant, μ is the coefficient of friction, σ_{ut} is the ultimate tensile strength, and ε is the elongation at break. So wear resistance of a composite is proportional to the ($H\sigma_{ut}\varepsilon$) product. For a particular load and sliding distance, relative wear resistance is measured as:

$$\text{relative abrasive wear resistance} = \frac{(H\sigma_{ut}\varepsilon)\text{ product of a composite}}{(H\sigma_{ut}\varepsilon)\text{ product of base composite}}. \tag{11}$$

Using the values of hardness, ultimate tensile strength, and elongation at break, relative wear resistance in abrasion is calculated and is given in Figure 14. In this case also, wear resistance is highest for the friction material with 20% alumina fiber content and it is 1.9 times that of the base composite. The composite with 20% alumina fiber content has highest ultimate tensile strength and strain at failure which indicates that, during sliding, more work will be required at the contact to disrupt the material.

Total wear resistance will be a combination of that in adhesion and abrasion which shows a steady improvement with the increase in alumina content. Hence it is beneficial to have higher alumina content from theoretical prediction.

CONCLUSIONS

1. With increases in the alumina fiber content in the friction composites, specific gravity and elastic modulus reduce.
2. Mechanical properties such as compressive strength, hardness, tensile strength, and shear strength improve with increment in alumina fiber content in friction composites.

3. Thermal analysis shows that glass transition and decomposition temperature of the friction composites vary slightly with increase in alumina fiber content.
4. The wear prediction shows that wear resistance of the friction materials improve with increase in alumina fiber content. The friction material with 20% alumina fiber is shown as having the highest wear resistance in adhesion as well as abrasion.

REFERENCES

1. Bijwe, J. (1997). Composites as Friction Materials: Recent Developments in Non-asbestos Fiber-Reinforced Friction Materials – a Review, *Polymer Composites*, **18**: 378–396.
2. Lemen, R. A. (2004). Asbestos in Brakes: Exposure and Risk of Disease, *American Journal of Industrial Medicine*, **45**(3): 229–237.
3. Blau, P. J. (1995). *Friction Science and Technology*, Marcel Dekker Inc., New York.
4. Roggli, V. L. and Langer, A. M. (2005). Asbestos in Brakes: Exposure and Risk of Disease, *American Journal of Industrial Medicine*, **47**(3): 276–277.
5. Chan, D. and Stachowiak, G. W. (2004). Review of Automotive Brake Friction Materials, *Automobile Engineering*, Part D, **218**: 953–966.
6. Durand, J. M., Jeandin, M. and Vardavoulias, M. (1995). Role of Reinforcing Ceramic Particles in the Wear Behavior of Polymer-based Model Composites, *Wear*, **181–183**: 833–839.
7. Eriksson, M. and Jacobson, S. (2000). Tribological Surfaces of Organic Brake Pads, *Tribology International,* **33:** 817–827.
8. Osterle, W. and Urban, I. (2004). Friction Layers and Friction Films on PMC Brake Pads, *Wear*, **257:** 215–226.
9. Gopal, P., Dharani, L. R. and Blum, F. D. (1995). Load, Speed and Temperature Sensitivities of a Carbon-fiber-reinforced Phenolic Friction Material, *Wear*, **181**–**183**: 913–921.
10. SAE J 380 SEP 93, SAE recommended practice for measurement of 'Specific gravity of brake lining'.
11. ASTM D638-01 Standard test method for tensile properties of plastics.
12. Bijwe, J. and Satapathy, B. K. (2004). Performance of Friction Materials Based on Variation in Nature of Organic Fibers-Part 1 Fade and Recovery Behavior, *Wear*, **257**: 573–584.
13. ASTM D732-99, Standard test method for shear strength of plastics by punch tool.
14. Burwell, J. T. (1957/58). Survey of Possible Wear Mechanisms, *Wear*, **1**: 119–141.
15. Alaya, J. E., Yang, A. C. M. and Scott, C. (1991). Abrasive Wear in Filled Elastomers, *Journal of Materials Science*, **26**: 2823–2837.
16. Briscoe, B. J. and Sinha, S. K. (2005). *Tribology of Polymeric Solids and their Composites*, pp. 223–268, In Stachowiak, G.W. (eds.) Wear – Materials, Mechanics and Practice, John Wiley and Sons, London.