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Experimental Investigation of Physical and Mechanical Properties of Steel Powder Filled Disc Brake Friction Materials

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ABSTRACT: *A suitable selection of a filler material enhances the mechanical and tribological characteristics of brake friction material. There are various types of fillers like organic, inorganic, metallic and natural fibres. Among these various types, metallic fillers are very important as they consist of different functional characteristics of brake friction material. Hence in this work, four friction composites are shown with identical parent composition (65 wt%) and varying steel powder from 0 wt% to 12 wt%, and barite from 35 wt% to 23 wt%, respectively in each composition, i.e., S0, S1, S2 and S3. All these four composites are characterised for physical and mechanical properties according to Indian Standards (IS). The coefficient of friction is investigated using a pin on disc tribometer. Finally, the correlation between physical properties and coefficient of friction is determined. It is concluded that inclusion of steel powder improved almost all the physical and mechanical properties. It is also observed that density, void content and hardness influence the coefficient of friction level.*

Keywords: Friction material, physical properties, hardness, steel powder, correlation

1. INTRODUCTION

There have been rapid developments in the automotive industry due to increasing demand for high speed and high engine power vehicles. For such commercial vehicles, the brake friction material is required to provide a stable coefficient of friction (COF) and a lower wear rate at various operating speeds, pressures, temperatures and environmental conditions. These friction materials must also be harmonious with the disc material to reduce its extensive wear and brake squeal phenomenon during braking.[1,2]

Friction composites can be classified into four main categories such as non-asbestos, organic, carbon-based and metallic friction composites. Nowadays, non-asbestos organic and metallic materials are predominantly used in the automotive industry. All these materials should be economical and eco-friendly. A commercial brake lining usually contains more than 10 to 25 different constituents. A selection of these constituents is often based on experience or trial-and-error-methods to make a new formulation.[3–5] These friction constituents can be divided into five categories, namely binders, abrasives, solid lubricants, functional reinforcements and space fillers. The common binding agent used in a friction material is a thermosetting polymer like phenolic resin and rubber. There have been deep studies related to the effect of straight phenolic resin and modified phenolic resin (phenolic resin modified with cashew nut shell liquid, linseed oil, alkyl modified resin, etc.) on performance characteristics, fade and recovery behaviour of brake friction material.[6–9] Due to health issues, asbestos friction materials are replaced by non-asbestos friction materials to a great extent. Study has also been done on the effect of various organic fibres like aramid, PAN, carbon and cellulose on the fade and recovery behaviour of friction composites.[10] The addition of the metallic ingredients like brass, iron, chromium and copper controls the wear and thermo-physical properties of the friction materials.[11–13] The main function of the solid lubricants is to maintain the constant level of friction. Various researchers studied the effect of different solid lubricants (graphite, antimony trisulphide, molybdenum disulphide, etc.) on the stability of coefficient of friction.[14–17] The precise mixture of the five constituents utilised in a friction material depends on wear rate, ranges of operating temperature and friction level needed. The operating temperature range of brake friction material is typically from 0°C to 650°C. At the higher temperature, the wear rate of the friction material increases exponentially.

Any ingredient, which is added to achieve a specific property of friction material, also influences other essential properties of the material in the desirable or undesirable manner as given in Table 1 to be studied.

Before friction characteristics are tested, friction materials must undergo testing of physical and mechanical properties. If tested, composites should give adequate performance. Only then, these friction composites are accepted. Measurement of physical properties of composites includes density, water swell, heat swell, hardness, tensile strength and loss of weight after ignition.

Table 1: Effects of different ingredients on performance characteristics of brake friction material.

Ingredient	Desirable effect	Undesirable effect
Phenolic resin[18]	Binder for matrix	Increases hardness Noise propensity increases
Graphite[15]	Medium temperature lubricant	Decomposes into gases after 700°C
Antimony trisulfide[15]	Lubricating agent	Stable up to 350°C Wear increases after 350°C
Magnesium oxide[13]	Increases coefficient of friction	Increases wear Noise propensity increases
Potassium titanate[13]	Reinforcing agent	Increases wear rate
Aluminium oxide[19]	Increases coefficient of friction	Increases pad wear
Iron oxide[19]	Increases coefficient of friction	Increases disc wear
Copper[19]	To control heat transfer	Increases disc wear
Calcium carbonate[19]	Low-cost space filler	Not stable at high temperature
Lead oxide[19]	Increases coefficient of friction	Toxic for human health
Copper sulphide	Stabilises friction film	Fluctuating coefficient of friction Worst wear
Aramid[21]	Wear resistant Fade decreases	Counterface temperature increases

Porosity is one of the important properties of composite materials as it influences other performance parameters of friction composites. Composites having higher density possess lower porosity. When the porosity is lower, the composite material has higher strength and thermal conductivity. Porosity also affects the water absorption. When the porosity is less, water absorption also decreases. Water swell drops the friction performance of friction material. Hardness is one of the significant mechanical properties of friction composites. As porosity increases, hardness reduces due to the decrease in resistant volume of mechanical stresses.[20,21]

Water swell is the measure of water absorption by friction composite. Heat swell is the absorption of heat or change in thickness after heating. Water swell and heat swell should be as minimum as possible as it affects braking effectiveness. Hardness is a significant parameter in the determination of abrasion resistance. It depends on the composition of friction material and its manufacturing method. Hardness can affect the wear of friction material. Tensile strength is the measure of maximum stress that material can withstand before the failure under tension.

The nature of failure differs according to the type of material (rubberised material, phenolic resin bonded material and sintered friction composites). A loss of weight after ignition test is carried out to measure the non-organic constituents present in friction composites. After this test, the heavily oxidised residue is formed, which can be further analysed to find out inorganic content in the friction material.

In the present work, four non-asbestos organic (NAO) friction composites are developed by varying steel powder and space filler, i.e., barite in a compensatory manner keeping the remaining composition constant. The present work mainly deals with the effect of steel powder on the physical and mechanical properties of disc brake friction materials. Friction performance is the main performance characteristic of any brake friction material. Finally, the correlation between the coefficient of friction of four composites and their physical properties is studied.

2. EXPERIMENTAL STUDY

2.1 Fabrication of Friction Composites

The four friction materials are fabricated using 12 ingredients. The base material consists of 11 ingredients without steel powder, i.e., S0. Other friction materials are manufactured keeping 10 ingredients weight percentage (wt%) constant, i.e., 65 wt% and varying steel powder at a range from 4 wt% to 12 wt% and barite at a range from 31 wt% to 23 wt% respectively in each composition, i.e., S1, S2 and S3. The basic composition containing a straight phenolic resin (10 wt%), functional fillers, such as alumina, graphite, vermiculite, iron oxide (41 wt%) and fibres, such as potassium titanate and aramid (14 wt%). Graphite act as a solid lubricant and alumina, iron oxide are used to enhance the coefficient of friction as they are abrasive in nature.

The ingredients are mixed in a shear type of mixer to ensure mechanical isotropy of the composites. The mixture is then placed into a mould supported by the adhesive coated back plate. Each mould cavity is filled with approximately 120 g of a mixture and then compressed in a compression moulding machine under a pressure of 8 MPa for 7 min to 8 min at the 150°C curing temperature. Then, pads are oven cured for 12 h to 14 h to cure the remaining resin content.

2.2 Characterisation of the Composites

2.2.1 Physical and mechanical properties

Composites are characterised for physical properties (density, porosity, water swell, heat swell and loss of weight after ignition at 800°C) and mechanical properties (tensile strength and hardness) as per IS procedure.

Density is calculated first by weighing the specimen in the air within the accuracy of 0.1 g, and then, specimen (Figure 1) is immersed in water at ambient temperature such that it would not touch the wall of the container and again the specimen is weighed. During the time of weighing the specimen in water, air bubbles adhering to the specimen are removed. Theoretical density of friction composite is calculated using the rule of mixture compared with experimental density to find out the void content of the composite materials. Void contents give the idea of porosity of the specimen. It is calculated by the following relation:

$$\%Void\ Content = \frac{Theoretical\ density - Actual\ density}{Theoretical\ density} \times 100$$

Figure 1: Friction material sample for density testing.

Weight loss after ignition is the reduction in weight after the heating of the friction material at 800°C and it is tested in accordance with 5.7 of IS 2742 Part 3. The first sample is weighed accurately in a previously ignited, cooled and weighed silica crucible. Then, the sample is introduced into the muffle furnace, which is maintained at 800°C and soaked for 2 h. Flying of dust is not allowed during the process.

Rockwell hardness is defined in terms of depth of penetration of a spherical indenter into the specimen. It is also a measure of resistance to indentation under loads. It is measured using digital Rockwell hardness tester (Figure 2) according to 5.2 of IS 2742 Part 3. The sample is placed on the support as shown in Figure 2. The load of 600 N is applied to the working surface of the specimen with a ball indenter diameter of 12.7 mm as it is Rockwell hardness R scale. Then, the readings are taken. A water swell test is carried out as per 5.6 of IS 2742 Part 3 and a heat swell test is carried out as per 5.8 of IS 2742 Part 3. The samples used for water swell test and heat swell test are as shown in Figure 3. Tensile strength is performed on friction composite as per ASTM D638. The sample for tensile strength is as shown in Figure 4.

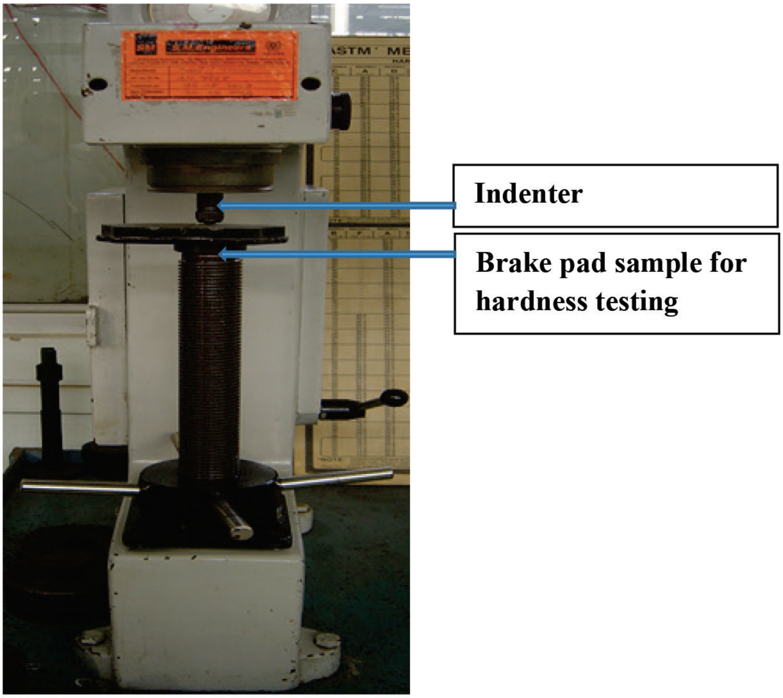

Figure 2: Rockwell hardness testing.

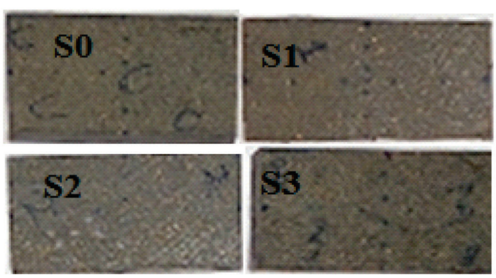

Figure 3: Friction material samples for water swell and heat swell testing.

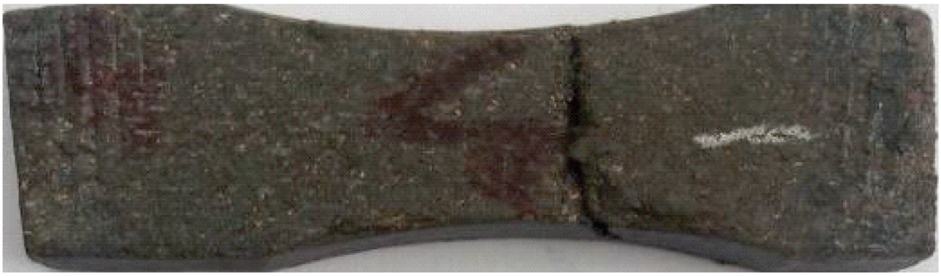

Figure 4: Friction material specimen after tensile testing showing failure.

2.2.2 Friction performance

The coefficient of friction is investigated using a pin on disc tribometer. The tests are conducted at an ambient temperature at a speed of 5 m s^{-1} with an applied load of 10 kg. Disc material is En 31 steel hardened to 60 HRC having surface roughness value 1.6 Ra.

2.2.3 Correlation analysis for physical properties and coefficient of friction

A second-order polynomial regression is used to find out the correlation between the two variables. In this work, a regression technique is used to determine the relationship between the coefficient of friction and physical properties. The coefficient of determination R^2 is determined, and it gives the proportion of variance of the coefficient of friction with respect to other physical properties (density, void content, hardness, tensile strength and loss of weight after ignition).

3. RESULTS AND DISCUSSION

3.1 Physical Properties

Density is first and foremost physical property of brake friction material. Determination of density and void content is essential for estimation of the quality of the friction composites. The density of the composites is in the range of 2.25 g cm^{-3} to 2.34 g cm^{-3} (Figure 5), and percentage void content is in the range of 14.5 to 17.81 (Figure 6). As the filler weight percentage (wt%) is increased, the density exhibited increasing trend from 2.25 g cm^{-3} to 2.34 g cm^{-3} and void percentage decreases from 17.81 to 16.97 (for S1 to S3 friction composites). The reason for this trend is a higher density of steel powder (7.89 g cm^{-3}) as compared to barite powder (4.2 g cm^{-3} to 4.3 g cm^{-3}). The highest percentage of void content is observed for base material S0. The high porosity helps to reduce brake noise and rotor wear. Brake noise arises in the friction composites with high values of coefficient of friction. Additional parameters that influence noise are sliding interface, porosity and hardness. The friction composites with low porosity and high hardness are likely to produce brake noise.

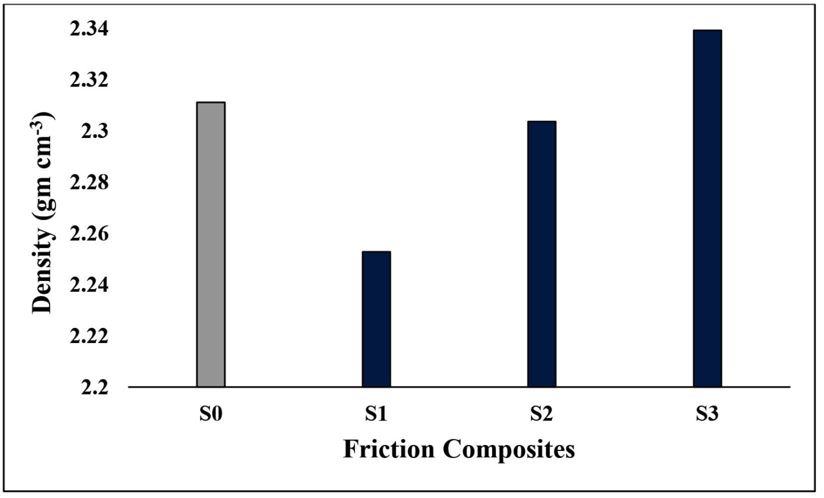

Figure 5: Effect of filler weight percentage on the density of friction composites.

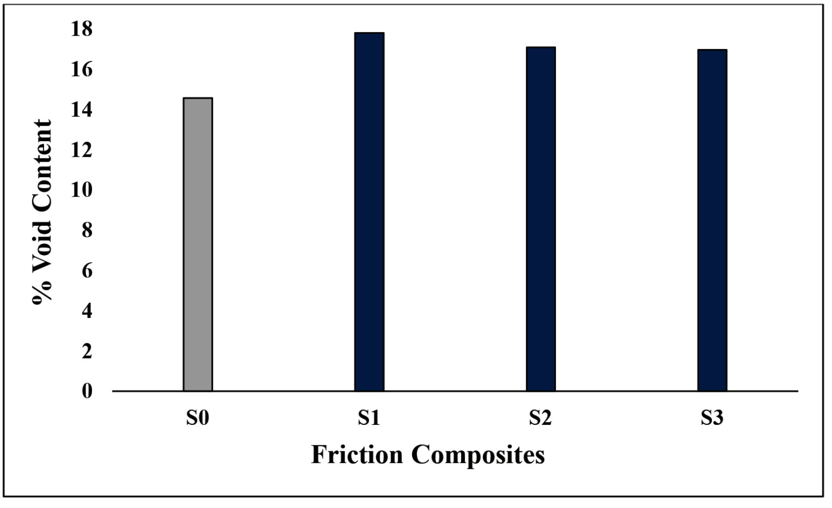

Figure 6: Effect of filler weight percentage on void content.

Nanfeldt suggested that an effective friction material should contain density elements to resist the normal loads experienced during braking. The dimensional stability of friction material at elevated temperature is essential as it influences wear. Heat swell gets increased as a weight percentage of steel powder is increased from 4% to 12% as shown in Figure 7. Water swell does not show any trend. In all the friction composites, water swell is less than 0.02 mm.

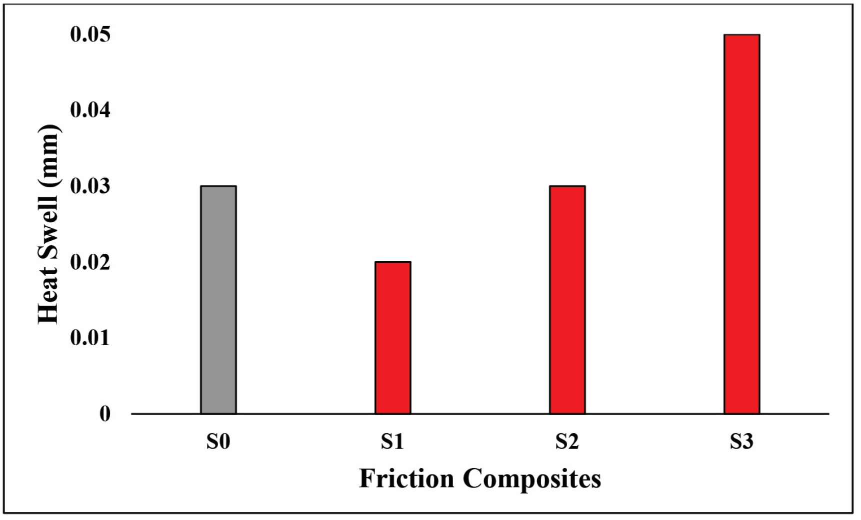

Figure 7: Heat swell as a function of composition.

The percentage of weight loss after ignition involves heating of powder at 800°C in the presence of oxygen. The less percentage of weight loss at higher temperature indicates less degradation of friction material at a higher temperature or material will give a stable performance at a higher temperature. As shown in Figure 8, the composite material without steel powder exhibits the highest loss of weight percentage and composite material with 12 wt% steel powder (S3), showing the lowest loss of weight percentage after ignition.

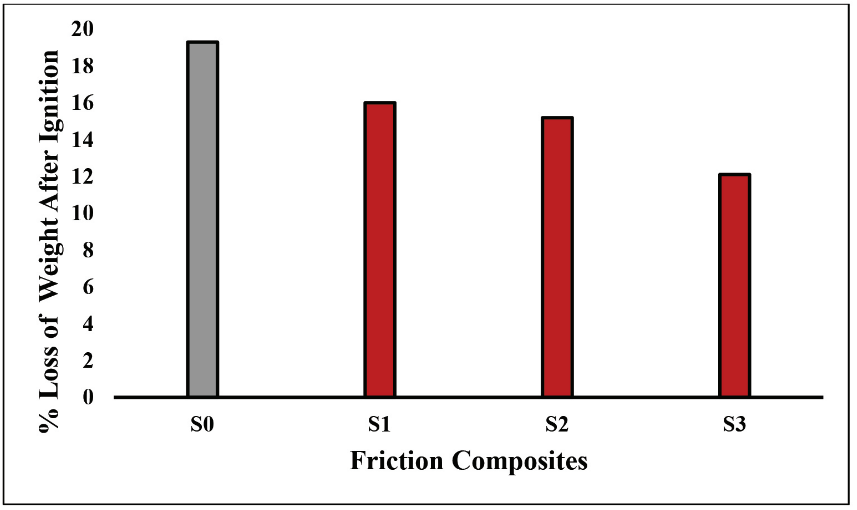

Figure 8: Effect of filler weight percentage on the loss of weight after ignition.

Hardness can be roughly correlated with density, as density increases, the hardness also increases. The hardness (Figure 9) increases with an increase in the weight percentage of steel powder and with a decrease in barite weight percentage. The Rockwell hardness HRR scale is amplified from 84.6 to 94.6 for S0 to S3, respectively. The reason behind the increasing trend of hardness value is the high hardness of steel (Mohs scale of 5 to 6.5) as compared to barite (Mohs scale of 2.5 to 3.5). Hardness is one of the most important parameters in the determination of abrasion resistance. Although it is not correlated with frictional output, it has been found to improve the wear resistance of friction material. The tensile strength (Figure 10) does not show any regular trend. The order of performance of tensile strength is as follows:

Tensile strength: S0 > S1< S2 > S3

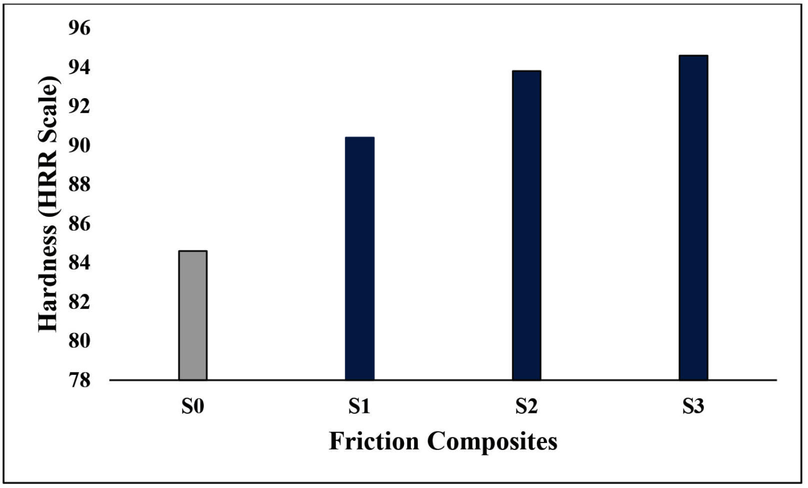

Figure 9: Effect of filler weight percentage on the hardness of friction composites.

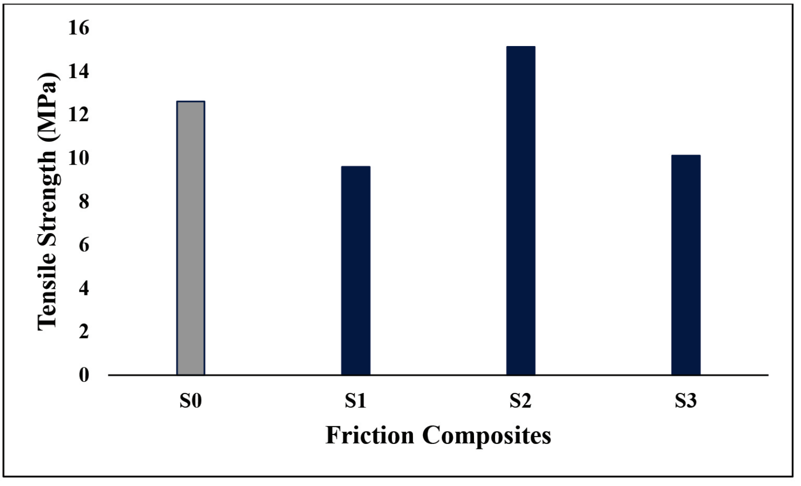

Figure 10: Effect of filler weight percentage on the tensile strength of friction composites.

3.2 Friction Performance of Composites

Friction performance of the steel powder filled composites is as shown in Figure 11. As the amount of steel powder is increased, the coefficient of friction also increases. The lowest COF is observed for S0, i.e., 0.39 and the highest COF is observed for S3, i.e., 0.44 composite having 12 wt% steel powder. Thus, steel powder enhances the friction performance of brake friction material.

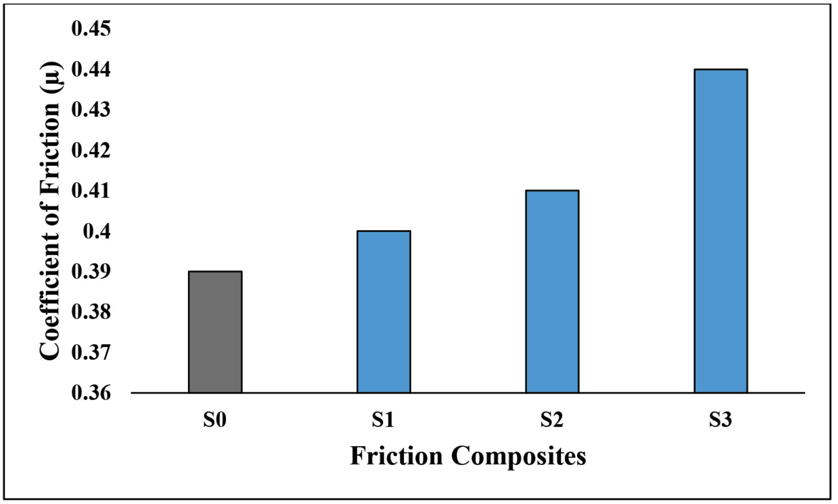

Figure 11: Effect of friction composition on the coefficient of friction.

3.3 Correlation of Physical Properties with Friction Performance

The correlations between the physical properties and the coefficient of friction of composite materials under the load of 10 kg and at sliding speed of 5 m s^{-1} are determined. In view of individual mechanical properties, figures show the correlation results of density (Figure 12), void content (Figure 13), hardness (Figure 14), loss of weight after ignition (Figure 15) and tensile strength (Figure 16) against coefficient of friction of S0, S1, S2 and S3, respectively. The correlation results show a significant correlation between hardness and loss of weight after ignition while the other physical properties also show significant correlation against coefficient of friction.

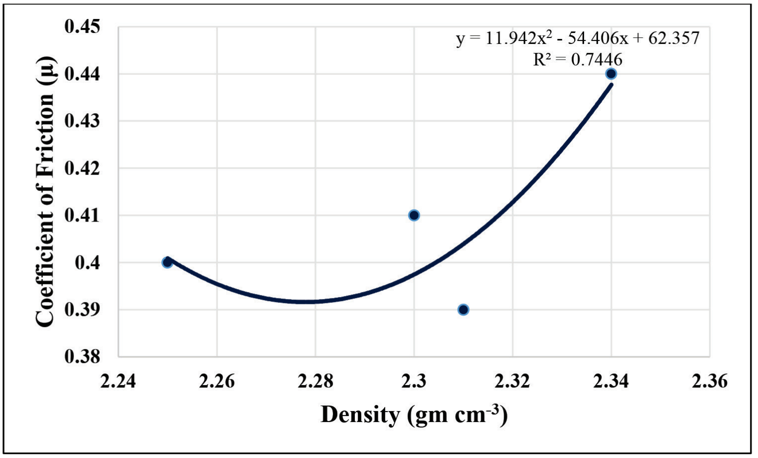

Figure 12: Effect of density on the coefficient of friction.

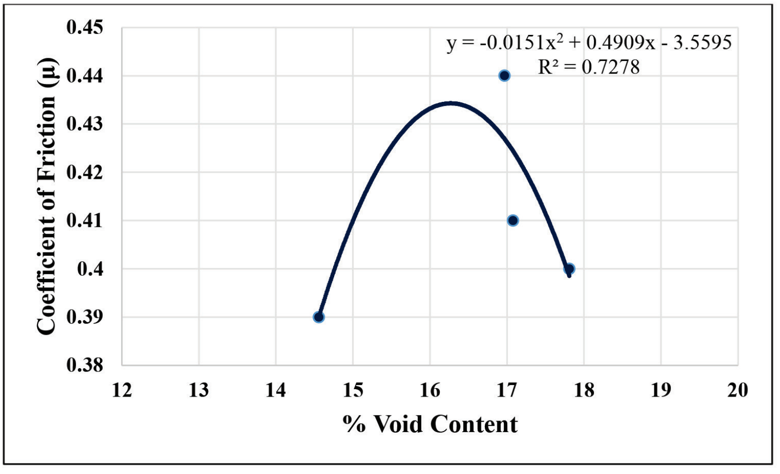

Figure 13: Effect of void content on the coefficient of friction.

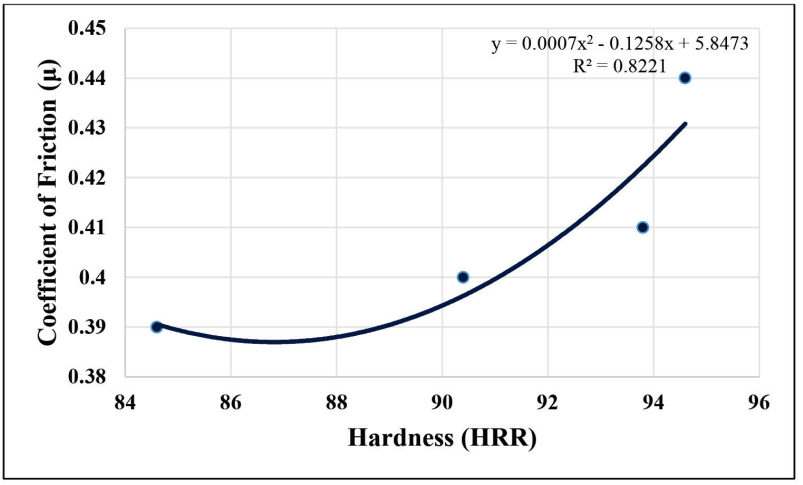

Figure 14: Effect of hardness on the coefficient of friction.

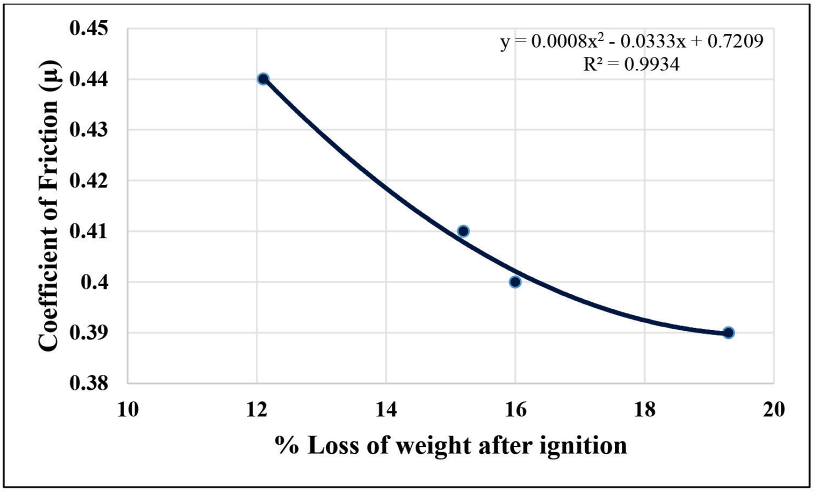

Figure 15: Effect of loss of weight after ignition on the coefficient of friction.

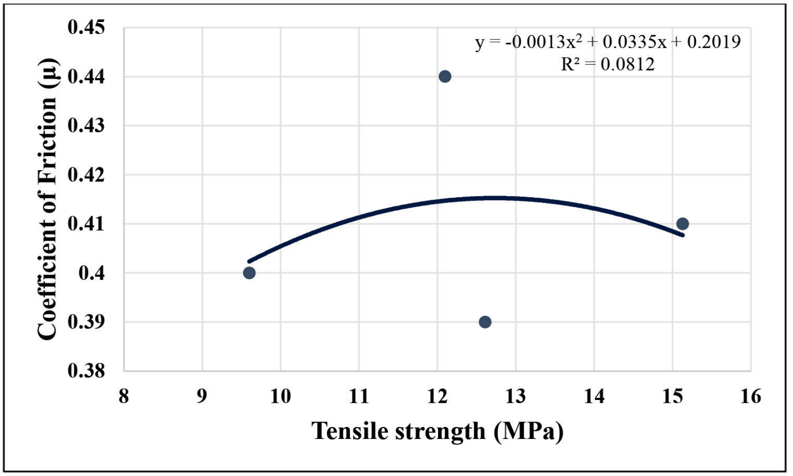

Figure 16: Effect of tensile strength on the coefficient of friction.

4. CONCLUSION

Steel powder filled disc brake pads have been fabricated and tested for their physical and mechanical properties. Based on the studies of these composites containing an increased amount of steel powder from 4 wt% to 12 wt%, the following conclusions have been drawn. As the amount of steel powder is increased, the density of the friction material also increases and percentage void content decreases. The increase in steel powder content leads to a decrease in loss of weight after ignition or ash content. Hardness is improved as a weight percentage of steel powder gets increased. It has been observed that the coefficient of friction is highest in the composite with the highest amount of steel powder, i.e., S3 and lowest was in the composite without steel powder, i.e., S0. The correlation results reveal that density, void content and hardness influence the coefficient of friction level. The presence of steel powder enhances the friction performance, physical and mechanical properties of disc brake friction material.

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