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RESEARCH

Tribological Performance of Brass Powder with Different Copper and Zinc Content in the Brake pad

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A B S T R A C T

Metallic fillers play a significant role in the brake friction material formulation due to its high thermal conductivity, tribo-load bearing ability against the rotor, friction stability and wear resistance. Brass powder is widely used in the formulation because of good thermal conductivity, fade and wear resistance. The commercial brass composed of 70 wt.% copper and 30 wt.% zinc. In this work, the brass powders with identical morphology and different weight percentage (wt.%) copper and zinc content is evaluated for its tribological and physico-mechanical performance in the brake friction material formulation. Three set of brake friction pads were fabricated with three different brass powders of varying copper and zinc content, 60% Cu-40% Zn, 70% Cu-30% Zn, and 80% Cu-20% Zn, respectively. The objectives of this study were to find the physico-mechanical properties based on Indian Standard IS 2742 and tribological performance of the brake pads based on ASTM G99-95 using pin-on-disc tribometer. The wear mechanism of the brake composite of worn surface was studied using scanning electron microscope. The brake friction composites were ranked based on extension evaluation method by considering the tribo-mechanical performance parameters. It is observed that brass with 80% Cu and 20% Zn proved to be the best performer based on the weighted average dependent degree of extension evaluation.

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1. INTRODUCTION

Brake is one of the important safety systems in the automobile, in which the disc and brake pad tribo pair is considered to be more effective than drum and liner type in terms of friction. The performance of brake system mainly depends on the friction between the brake pad and the disc [1]. The material in contact decides the friction between the tribo pair. As the temperature increases during braking, the bonding of the material used for making the brake composite should be strong enough to avoid quick wear and deterioration of friction performance in order to accomplish multiple functions [2]. These materials are classified as binders, fibers, friction modifiers (abrasives and lubricants) and fillers [3,4]. Many works have been carried out in demonstrating the importance of these materials towards friction and wear performance. Several hundreds of materials have been studied to attain better tribological performance. Metallic brake pads containing metals having good thermal conductivity were used to improvise the tribo performance followed by semi-metallic brake pads and non-asbestos organic brake pads (NAO) [5-7].

Thermal conductivity of friction composite plays a vital role in tribo performance during braking. Low thermal conductivity leads to degradation of week ingredients and high thermal conductivity affects the brake fluid performance. Bijwe et al [8] have investigated the effect of brass content (0 wt.%, 4 wt.%, 8 wt.% and 12 wt.%) on the tribological performance of NAO brake pad formulation. The results concluded that the brake composites with 8 wt.% brass content exhibit better tribological performance. Mukesh Kumar et al., [9] conducted an experimental study using reduced scale prototype (RSP) and inertia brake dynamometer. The objective was to evaluate the tribological performance with addition of metallic contents like copper, brass and iron, in the form of powders and fibers in the brake friction composite formulation. It is inferred that, the composites containing brass had moderate level of wear and friction performance between copper and iron. Copper provides good brake performance properties and thermal conductivity. Also, copper plays dual role; one as a reinforcing element providing contact sites by forming primary plateaus and secondly as high temperature solid lubricant by contributing to the formation of a layer of granular material providing velocity accommodation between the rotating disc and fixed pad [10]. Very few studies report the effect of zinc powder on wear performance of the brake composite. Boz and A.Kurt [11] have studied the effect of zinc content (0.5-5 %) in the bronze based sintered brake pad, tested under the standard SAE J661a. The study inferred that the 2 % zinc content has improved the friction performance of the brake pad. Further increase in zinc above 2 % improves wear resistance by reducing the fade performance of the brake which is essential. The effect of brass (an alloy of copper and zinc) powder content on the tribological performance of NAO brake composite was evaluated by Sellami et al. [12] and found that the addition of inferred that the samples with 4.5 % created plateaus and conversely if added less than 4.5% brass improved the wear performance. They also removed the material from the matrix implying a higher source of third body wear.

The brass used by predecessor in their brake composition has 70 wt. % copper and 30 wt. % zinc. With this in view, an attempt has been made to study the effect of varying wt. % of copper and zinc content in the brass powder towards the tribological performance in the composition of brake friction composite. The two modified brass composition were taken for this study and compared with commercially used brass powder.

2. Materials & Methods

2.1 Materials

The commercial brass alloy composed of copper and zinc of 70 and 30 percentage by its weight (wt.%), respectively. In this work, the brass alloy was modified for two more compositions. One was with 60 wt.% of copper and 40 wt.% of zinc and another was 80 wt.% of copper and 20 wt.% of zinc. The commercially available brass and its modified version powder was prepared and supplied by Innomet powders Co. Ltd. The morphology and chemical composition of the powders were studied using Scanning Electron Microscope (SEM) of model FEI QUANTA FEG200 equipped with Energy Dispersive X-ray Spectroscopy (EDS). Since the brass powder is conductive in nature, the test was conducted in the high vacuum mode with the input of 15 kV. The EDS analysis is a semi quantitative technique used to identify the chemical element composition of the specific point or area. In this study the imaged area was taken for EDS analysis with the energy range 0-15 keV. The morphology of the brass powders at 400x magnification is shown in Fig. 1 (a-c). The morphology of the brass powders has not reveal much difference. The EDS analysis shows the presence of the Cu and Zn in the brass powder as shown in (Fig. 1 (a_1-c_1)). The variation of the Cu and Zn content in terms of normalized mass % is shown in the Table 1. It clearly indicates the Cu to Zn ratio increases from sample S1 to S3.

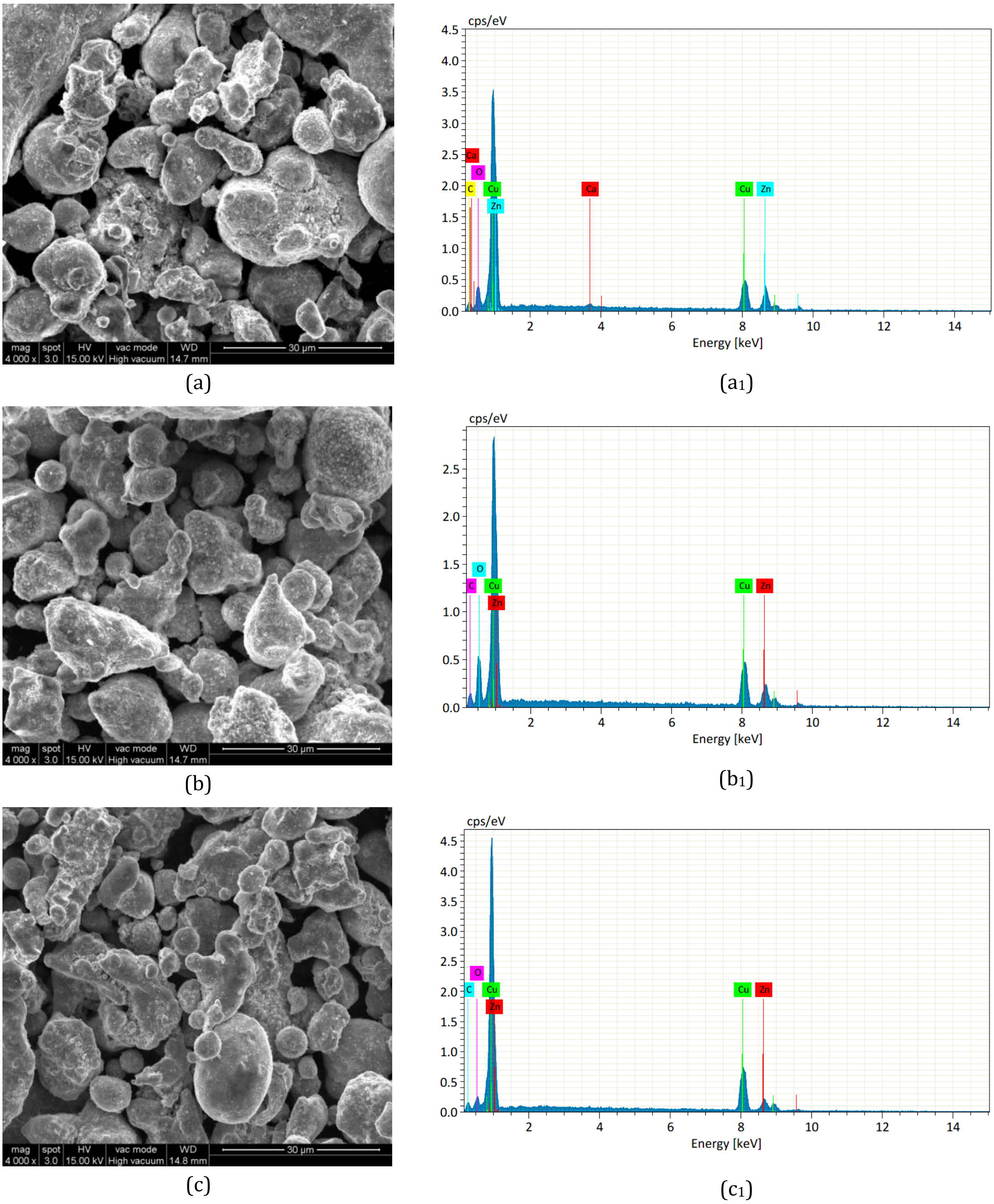


Fig. 1. SEM morphology of the brass powder with, (a) Cu 60 % and Zn 40 %, (b) Cu 70 % Zn 30 % (c) Cu 80 % Zn 20 % and EDS of brass powder with (a_1) Cu 60 % and Zn 40 %, (b_1) Cu 70 % Zn 30 % (c_1) Cu 80 % Zn 20 % .

Table 1. EDS analysis element composition as normalized mass percentage.

SAMPLE	Cu	Zn	O	Cu/Zn
Brass (Cu 60 %, Zn 40 %)	45.66	41.59	5.67	1.09
Brass (Cu 70 %, Zn 30 %)	52.06	31.38	9.04	1.23
Brass (Cu 80 %, Zn 20 %)	67.90	22.20	2.94	2.74

2.2 Friction Material Formulation

Three friction material sample formulation was prepared by keeping 95 wt.% of materials as a constant parent ingredient. The parent composition consists of Molybdenum Sulphide (MoS_2) 3 wt.%, graphite 15 wt.%, Resin 10 wt.%, Zirconium silicate 4 wt.%, steel fiber 30 wt.%, and Baryte 23 wt.%, Wollastonite 10 wt.%. The remaining 5 wt.% is balanced by adding brass powder of different copper and zinc content were marked as S1, S2, and S3 are presented in Table 2.

Table 2. Brake pad compositions.

	S1	**S2**	**S3**
Ingredients	**Wt. (%)**	**Wt. (%)**	**Wt. (%)**
Resin	10	10	10
Barytes	23	23	23
Wolostonite	10	10	10
Graphite	15	15	15
MoS2	3	3	3
Zirconium silicate	4	4	4
Steel fiber	30	30	30
Brass (Cu 60 % Zn 40 %)	**5**	**0**	**0**
Brass (Cu 70 % Zn 30 %)	**0**	**5**	**0**
Brass (Cu 80 % Zn 20 %)	**0**	**0**	**5**
Total	100	100	100

2.3 Fabrication of Friction Composite Materials

The brake friction composites with different brass contain various copper and zinc content are manufactured by a compression molding technique [13,14]. The composition containing the fixed parent formulation and varying ingredients as shown in Table 2 were mixed using shear mixing machine. The glued backing plate was inserted in the die of Tata Indica brake pad. The composition mixture of 120 gm was weighed and filled in the die and cured in the die set up along with the backing plate at 163 °C for 8 min with 3 intermittent breathing cycles for volatile removal [15,16]. Post curing was done in an oven at 160°C for 5 hours as shown in Fig. 2. The friction material was removed from the back-plate of the brake pad to make the pin of 10 mm diameter for the wear performance test [17-19].

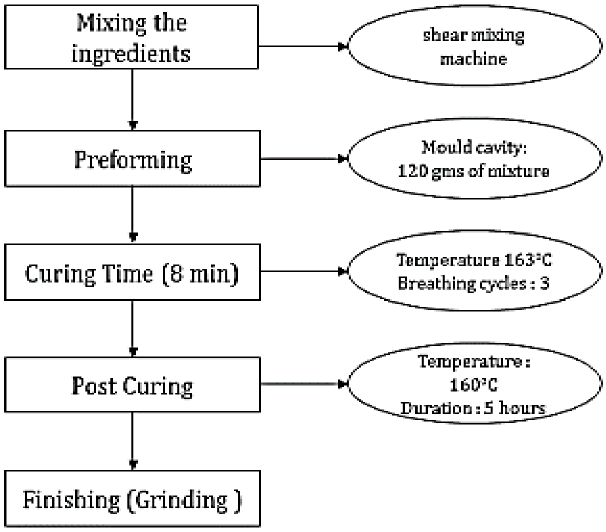


Fig. 2. Fabrication Process of Brake pad.

2.4 Pin on disc test

The friction and wear performance of the brake pad were tested in pin on disc setup (Fig. 3) (Ducom wear tester TR201CL) connected to the computer via data acquisition system. The material of the disc selected for friction surface was grey cast iron of 140 mm diameter and 8 mm thickness [20]. Table 3 shows the details regarding load, sliding speed and the specimen.

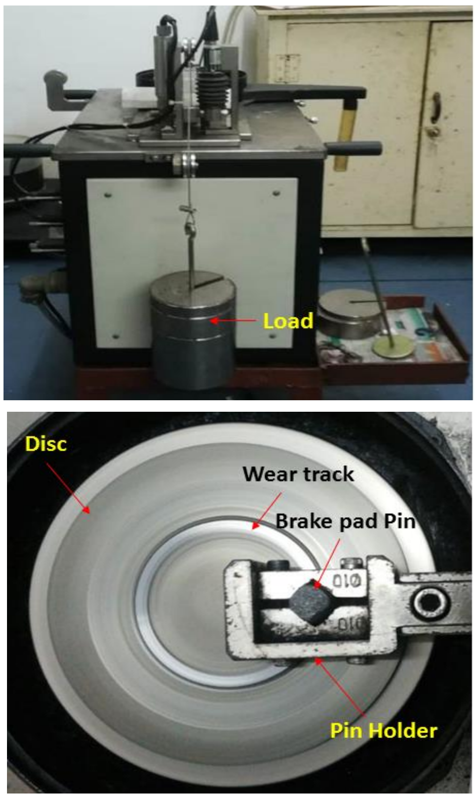


Fig. 3. Pin on disc setup.

Table 3. Load and sliding speed.

Sample	Varying parameters		
	velocity (m/s)	Load (N)	Sliding distance (m)
S1 (Cu 60% Zn 40%)	1	30	3000
		50	3000
		80	3000
	2	30	3000
		50	3000
		80	3000
	3	30	3000
		50	3000
		80	3000
S2 (Cu 70% Zn 30%)	1	30	3000
		50	3000
		80	3000
	2	30	3000
		50	3000
		80	3000
	3	30	3000
		50	3000
		80	3000
S3 (Cu 80% Zn 20%)	1	30	3000
		50	3000
		80	3000
	2	30	3000
		50	3000
		80	3000
	3	30	3000
		50	3000
		80	3000

3. RESULTS & DISCUSSION

3.1. Characterization of the Brake Pads

The physical, chemical, thermal and mechanical properties of the brake pads are given in Table 4. The density and porosity of the developed brake pads has negligible variation due to the modification of copper and zinc content of the brass. The hardness of the sample is varying from 80 to 94, depends on the indenter location on the surface of the brake pads. The cold shear strength of the brake pads is repeated for 4 times to check the consistency. The results of each sample tested are tabulated in Table 4.

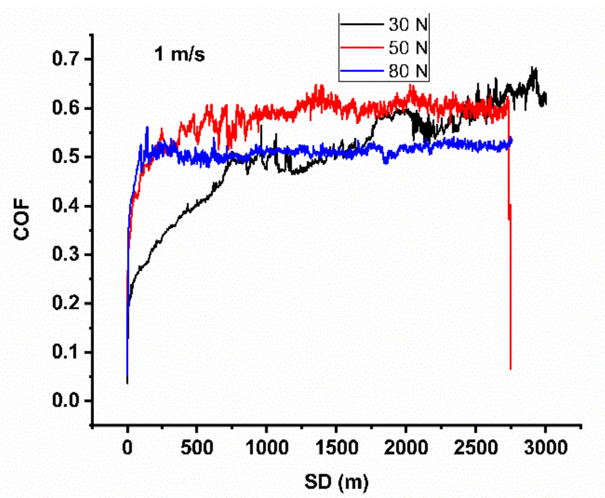
The shear strength is not having much significant variation among the samples. The thermal conductivity of the sample is much influenced by the copper content of the brass powder. The brass powder containing 80 % copper in the brake friction composite provides higher thermal conductivity compared to the brass powder with 60 % copper. The water and heat swell and acetone extraction (lower is better) values are well below the recommended values of the original equipment manufacturers (OEMs).

Table 4. Physical, Chemical, Thermal and Mechanical Properties of the brake pads.

Parameters	S1	S2	S3
	Cu60 – Zn40	Cu70 – Zn30	Cu80 – Zn20
Density (g/cm³)	2.12	2.17	2.23
Porosity (%)	6.1	6.9	6.2
Hardness (S-scale)	80-86	85-90	89-94
Cold Shear strength (kg/cm²)	29-31	30-34	30-32
Thermal conductivity (W/(m K))	1.7	2.06	2.22
Heat swell at 200 ⁰C (mm)	0.07	0.045	0.052
Water swell at room temperature (mm)	Nil	Nil	Nil
Loss of Ignition at 850 °C (%)	11.06	12.3	12.88
Acetone extraction (%)	0.41	0.32	0.57

3.2. Friction Performance

Figure 4 shows the coefficient of friction (μ) with respect to sliding distance under different load conditions (30 N, 50 N and 80 N) at a constant speed of 1 m/s, 2 m/s and 3 m/s for the samples S1, S2 and S3. From Fig. 4c, at 50 N load, the increase and decrease of the CoF is due to the friction film formation or three body rolling contact. For sample S1, μ is stable at high load and unstable at other loads [21].



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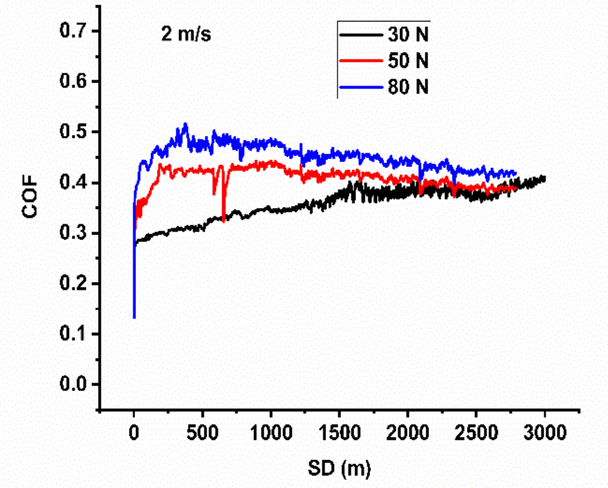

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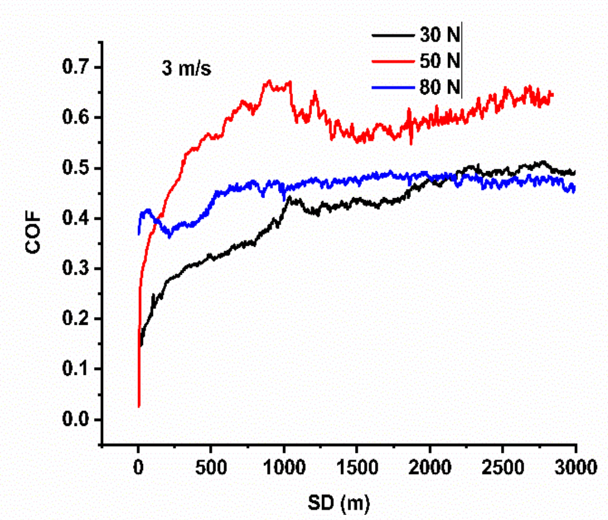
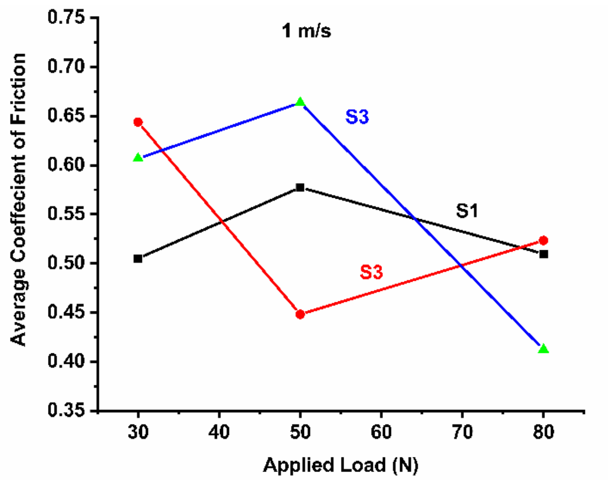


(c)

Figure 4. Coefficient of friction Vs Sliding Distance of sample S1 at (a) 1 m/s (b) 2 m/s (c) 3 m/s.

Figure 5a shows the average coefficient of friction of the sample S1 varying from 0.357 to 0.58. The average CoF increases upto the load 50 N and decreases at 80 N. For samples S2 and S3, under most of the loading condition, the low speed (1 m/s) provides higher CoF and high speed (3 m/s) provides low CoF. This is due to the rapid increase in the interface temperature with increasing speed. At 3 m/s speed, the sample S3 provide the higher CoF upto the load of 50 N compared to S2 and S1. The higher copper content of S3 provide better thermal conductivity and retain the CoF upto 50 N load condition.

The sample S2 has a different trend in the CoF with S1 and S3. The essential difference is mainly based on their crystal structure because of the combination of Cu and Zn which is characterized by peritectic solidification, with dissimilar atomic structures depending upon the Cu and Zn ratios and temperatures. S2, with 30% Zn content is also called as alpha brass because of their homogeneous (alpha) crystal structure. Hence, it offers softness and more ductility than their counterparts. Because of their ductility, they undergo elastic and plastic deformation as the load increases causing decrease in μ. But as the deformation continues as load increases, they increase the real area of contact which in turn increases μ. The COF of S1 and S3 increase upto 50N load and then decrease. The brake sample S3 comes under the class of alloy with 40 % or more zinc content. They form a beta crystal structure which is harder and stronger than both the alpha and alpha-beta brasses. The initial increase in μ is attributed towards their inherent hardness which increased resistance to deformation. This rigidness with poor flexibility, causes reduction in μ as load increased because of insufficient area of real contact.



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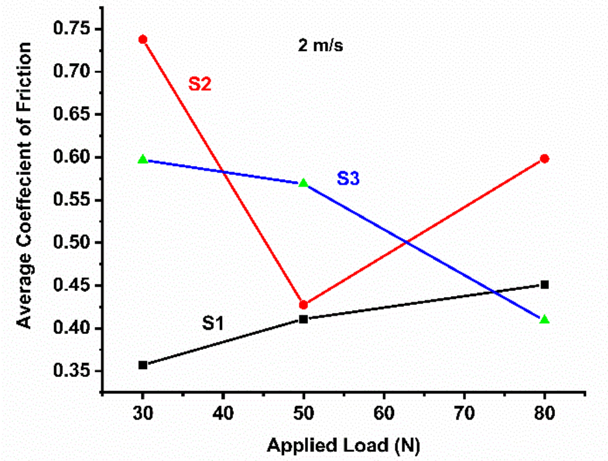

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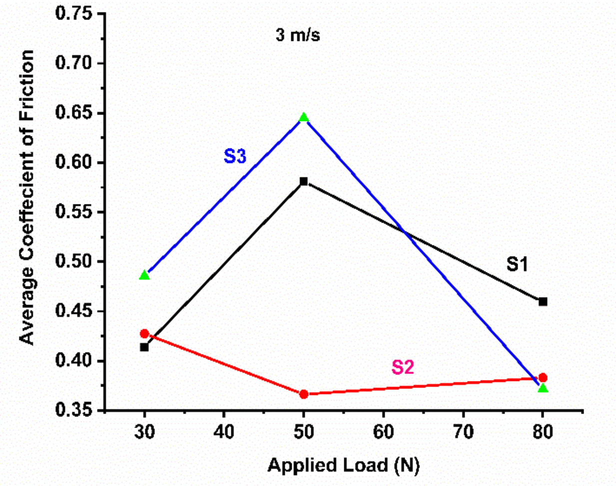


(c)

Fig. 5. Average Coefficient of friction Vs Applied load of sample (a) 1 m/s, (b) 2 m/s and (c) 3 m/s.

The reduction of CoF with respect to load and speed takes place in the sample S2 and S3. When load is considered, the samples with medium (70 wt.%) and high (80 wt.%) copper content brass powder (i.e., S2 & S3) are unstable whereas, at high load, low (60 wt.%) and high Cu content is stable. At high speeds, low Cu content brake pad (60-40) S1 and high Cu content (80-20) brake pad S3 are fluctuating. This fluctuation may be due to the following reason:

a) Unlike other metal fibers, Cu and its alloy powders are softer and less aggressive against the rubbing part [22]. The softness of the copper may be the reason for CoF reduction at high load conditions.

b) In the case of high Cu content i.e. 80 wt.% in S3, as the speed increases, kinetic energy increases and upon application of load, more work is done in converting kinetic energy into frictional heat energy. Cu being in excess, when compared to 60-40 (S1), has more thermal conductivity [5], which permits rapid increase in temperature which is followed by dissipation of heat by conduction through the pin which results in degradation of softer organic composites [23]. Moreover, Cu is helpful in the formation of friction films due to its moderate melting point and ductility which in turn promotes real area of contact to generate high μ. As Cu is excess in alloy 80-20 than 60-40, possibility of increased plateau formation is responsible for highest μ which is recorded as 0.64. But the increase is not consistent as observed from the graph (figure 5 (S3)). This is similar to the work carried out by Kumar [3], where the decrease in μ is correlated to the glaze formation to the disc. In addition, the friction temperature rise by increased speed reduces the surface mechanical property as found by [24,25]; even surface softening but invariably increases the resistance to deformation. Moreover, presence of steel fiber abrades the friction film formed which was responsible for μ stabilization [17].

3.2.1 Speed and load sensitivity

The friction fluctuation ($\Delta\mu$) is calculated as the difference between the maximum COF and its minimum by varying speed ($\Delta\mu_S$) and load ($\Delta\mu_L$). Table 5 shows the friction fluctuation ($\Delta\mu_S$ – speed sensitivity) for all the samples at different load by varying the speed of sliding. The speed sensitivity was observed to be maximum at 50 N and minimum at 80 N for sample S1. The sample S3 was observed to be relatively better by showing the less speed sensitivity, this could be the cause, due to the improved thermal conductivity of S3 with high copper content. The friction fluctuation due to load ($\Delta\mu_L$ – load sensitivity) is displayed in Table 6. The sample S2 showed high and S1 showed low sensitivity. A similar trend was observed with sample S3 with varying load and speed.

Table 5. Friction fluctuation-speed sensitivity ($\Delta\boldsymbol{\mu}_s$).

Sample	Load (N)	$\Delta\mu_S$
S1	30	0.148
	50	0.170
	80	0.058
S2	30	0.310
	50	0.082
	80	0.215
S3	30	0.121
	50	0.095
	80	0.041

Table 6. Friction fluctuation-load sensitivity ($\Delta\boldsymbol{\mu}_L$).

Sample	Speed (m/s)	$\Delta\mu_L$
S1	1	0.072
	2	0.093
	3	0.166
S2	1	0.195
	2	0.310
	3	0.061
S3	1	0.251
	2	0.187
	3	0.273

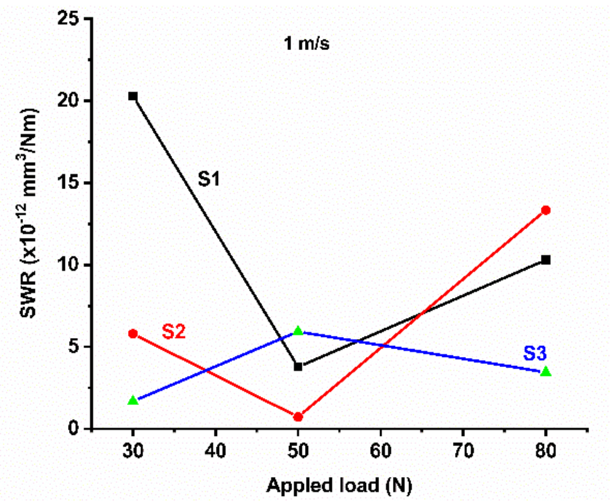
3.3 Wear Performance

Specific Wear Rate (SWR in mm^3/Nm) of the brake pad sample is calculated by using equation 1. The SWR for samples S1, S2 & S3 were shown in figure 6. Figure 6(a-c) shows, wear for all samples was less at 1 m/s speeds when compared to higher speed (2 m/s, 3 m/s) conditions. Similarly the low load (30 N) causes less SWR in all the cases compared to higher load (50 N, 80 N) conditions [26]. When comparing the SWR among the samples, significant difference was observed in terms of wear performance.

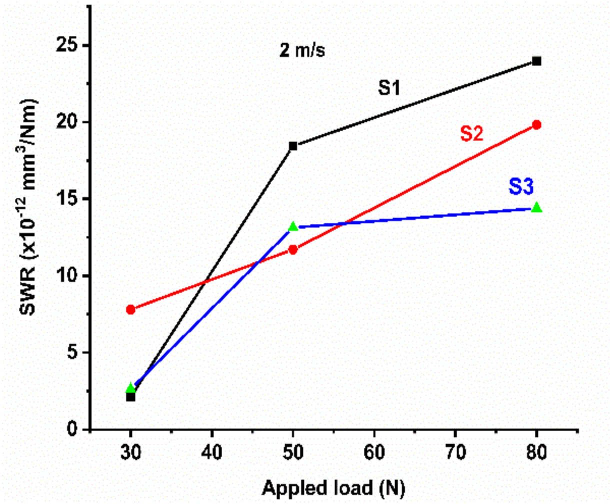
$$SWR = \frac{change\ in\ volume}{load\ \times Sliding\ distance} \qquad (1)$$

It was observed from the Fig. 6a, the specific wear rate of the sample S1 and S2 was high at the low speed (1 m/s) and low load condition, because of the higher contact between the polymer composite (brake pad) and disc material [24] . This higher contact and high zinc content of sample S1 and S2 increases the abrasion and subsequent wear at the interface. Whereas at the high speed condition, the contact between the polymer composite (brake pad) and the disc material is relatively less.

The sample S3 has reduced wear at the high load (80 N) condition compared to medium (50 N) load. The thermal softening of the material reduce the CoF at high load condition and subsequently reduce the SWR as well. Sample S1 and S2 has high zinc content than S3. The harder zinc is acting as a ploughing member at the interface for friction stabilization and wear faster relative to copper.



(a)



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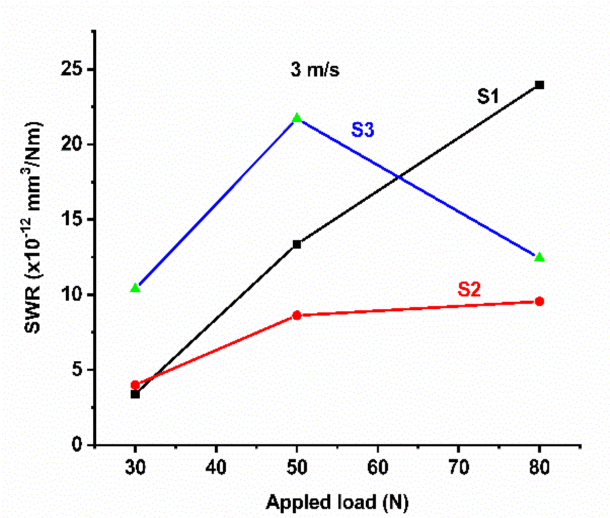

(c)

Fig. 6 Variation of SWR with Load applied (a) 1 m/s, (b) 2 m/s and (c) 3 m/s.

The worn surface morphology and elemental mapping of the surface of the samples S1, S2 and S3 were shown in Figs. 7, 8 and 9 respectively. The worn surface has appeared with the primary contacting plateaus A, majorly containing the Fe elements [27], which represents that the steel fibers are the major frictional load-bearing member in the formulation. The carbon is uniformly present on the entire wear surface which represents the graphitic carbon on the wear surface. This confirms the uniform lubrication on the work surface to maintain the friction film and reduce the friction fluctuations [28,29]. The brass particles are represented with the elements Cu and Zn on the worn surface. The brass particles are well dispersed on the surface and improved the conductivity of the tribo layer.

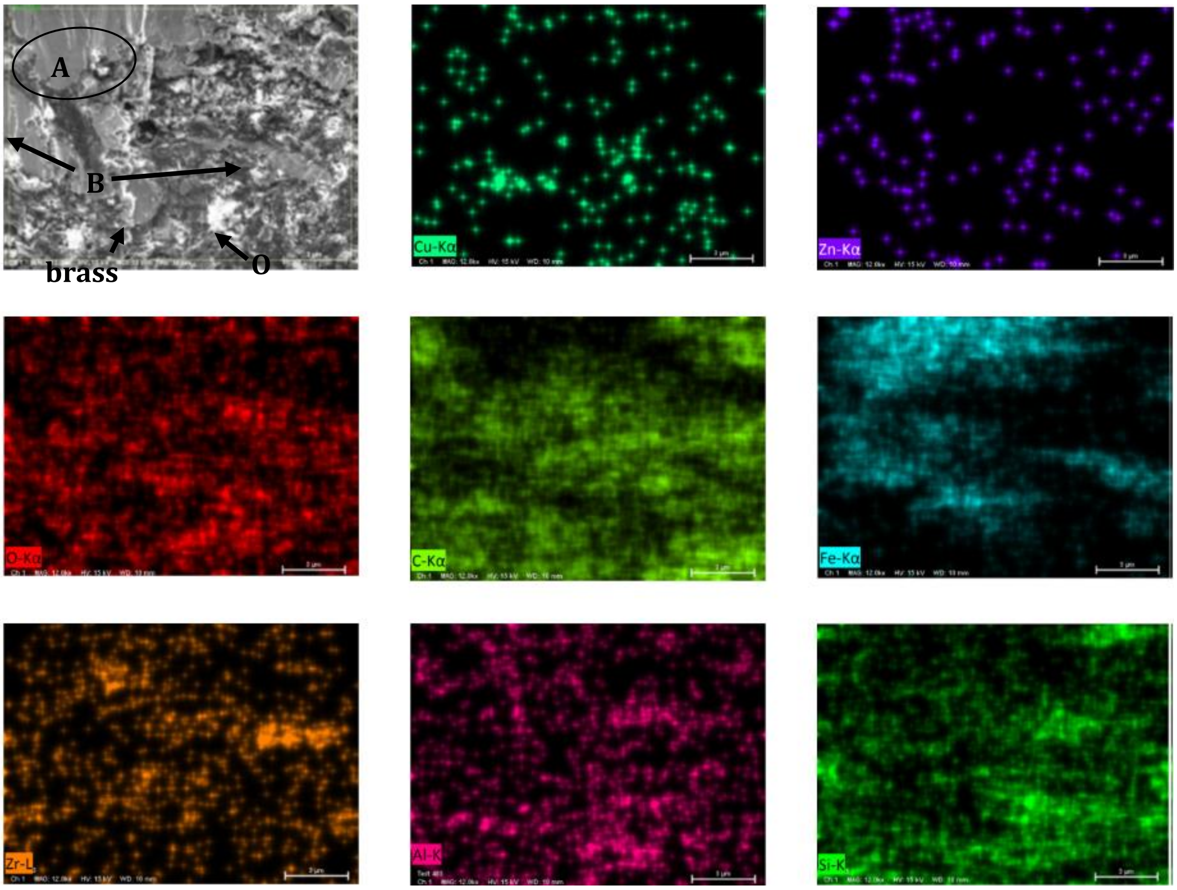

Fig. 7. EDS elemental mapping of the worn surface of sample S1.

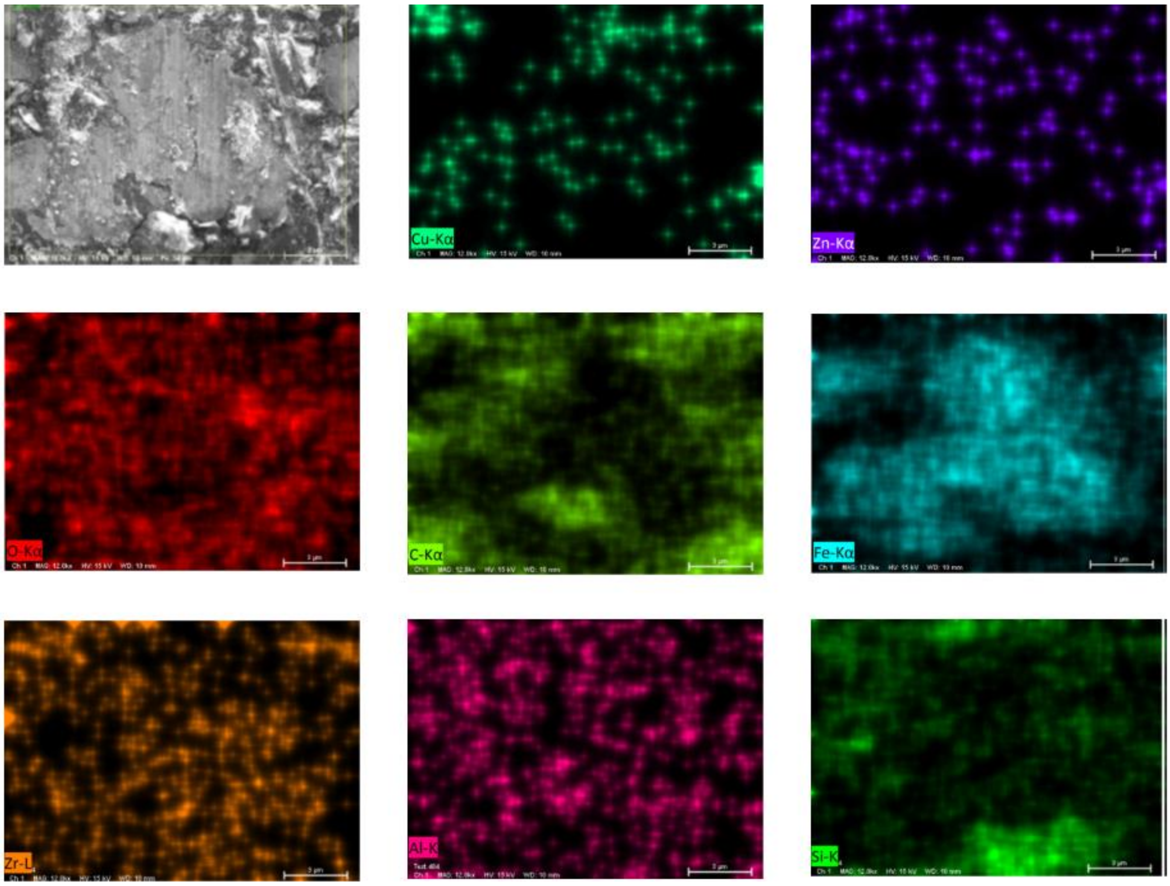

Fig. 8. EDS elemental mapping of the worn surface of sample S2.

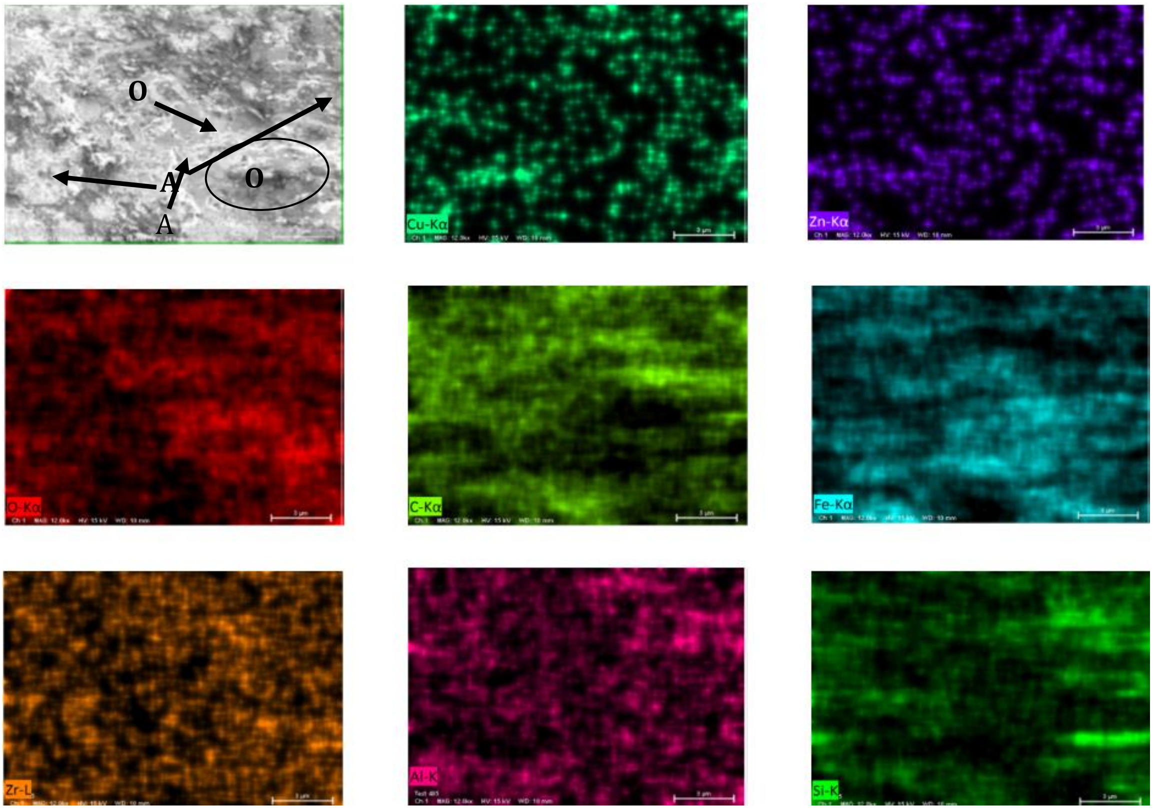

Fig. 9. EDS elemental mapping of the worn surface of sample S3.

The abrasives such as zirconium silicate and the alumina were uniformly present over the secondary tribo layer B of the wear surface. The worn surface is oxidized heavily due to the tribo-oxidation [30]. The oxidized films are marked as O which are weakening the friction film and increases the wear rate of the composite. The primary plateaus are smoother and appearing of the tribo grooves is less. So it is interpreted that the adhesive wear and tribo-oxidation are majorly dominating in the wear mechanisms of the samples. Hence the improved copper content of the sample S3 has less oxidation on its surface due to its high thermal conductivity of the sample compared to other samples.

3.4. Extension Evaluation of Ranking

The brake pads are proving the nonlinear relation between friction, wear, physical, mechanical and thermal properties. Therefore ranking the brake pads using the multiple parameters is essential. Extension evaluation based on extension theory is used in this study to rank the brake pads [31,32]. The brake pads were ranked based on 9 parameters represented in Table 7. The ranking of brake pads based on the weighted dependent degree $(\overline{K(x)})$ of the extension evaluation method. The dependent degree K(x) is calculated based on the equation 2. Where the interval X is belongs to (a,b) and the optimum expected performance point (M) lies in the interval X, i.e. $M \in X$. The dependent degree index $K(x)$ has four properties which are discussed in [18,33].

$$\boldsymbol{K(x)} = \begin{cases} \dfrac{\boldsymbol{x-a}}{\boldsymbol{M-a}}, & \boldsymbol{x \le M} \\ \dfrac{\boldsymbol{b-x}}{\boldsymbol{b-m}}, & \boldsymbol{x \ge M} \end{cases} \tag{2}$$

The multiple performance parameter considered for the ranking, its interval and the optimum point is listed in the Table 7. The parameters such as Friction, Cold shear strength, Thermal conductivity, are required to be as high as possible. The optimum point is the right limit (b) of the interval X. So the dependent degree is calculated based on equation 3.

$$\boldsymbol{K(x)} = \begin{cases} \dfrac{\boldsymbol{x-a}}{\boldsymbol{b-a}}, & \boldsymbol{x} < b \\ \boldsymbol{0 \vee 1}, & \boldsymbol{x = b} \\ \dfrac{\boldsymbol{b-x}}{\boldsymbol{b-a}}, & \boldsymbol{x} > b \end{cases} \tag{3}$$

The performance parameters such as wear, porosity, heat swell, loss on ignition and acetone extraction are required to be minimum to attain the optimum performance so the dependent degree is calculated based on equation 4.

$$\boldsymbol{K(x)} = \begin{cases} \dfrac{\boldsymbol{x-a}}{\boldsymbol{b-a}}, & \boldsymbol{x} < a \\ \boldsymbol{0 \vee 1}, & \boldsymbol{x = a} \\ \dfrac{\boldsymbol{b-x}}{\boldsymbol{b-a}}, & \boldsymbol{x} > a \end{cases} \quad (4)$$

The optimum performance of the parameter hardness is achieved at the midpoint the interval. The higher hardness leads to aggressive towards rotor and the lower hardness leads to increased wear of the brake pads. So the midpoint is considered as an optimum performance parameter. The dependent degree of the hardness is calculated based on equation 5.

$$\boldsymbol{K(x)} = \begin{cases} \dfrac{\boldsymbol{2(x-a)}}{\boldsymbol{b-a}}, & x < \dfrac{\boldsymbol{a+b}}{\boldsymbol{2}} \\ \dfrac{\boldsymbol{2(b-x)}}{\boldsymbol{b-a}}, & x \geq \dfrac{\boldsymbol{a+b}}{\boldsymbol{2}} \end{cases} \quad (5)$$

The dependent degree of each parameter belongs to the sample S1 is shown in the Table 8. Many techniques like expert scoring methods, AHP can be used to find the weighed dependent degree $\overline{K(x_i)}$. In this study the parameters are equally weighed for calculating the weighted mean of the dependent degrees based on equation 6. Where w_i is equal to 1/9.

$$\overline{\boldsymbol{K(x)}} = \sum_{i=1}^{9} \boldsymbol{w_i K(x_i)} \quad (6)$$

The weighted dependent degree represents the overall performance of the brake pads. The rank based on the weighed dependent degree represents the S3 with 80 % copper and 20 % zinc performs well compared to S2 and S1. The sample S1 with 60 % copper and 40 % zinc is the least performer.

Table 7. The parameters, limits and optimum points of the Extension Evaluation.

x_i	Descriptions	limit ranges for the interval Xi (a-b)	Optimum point M_i	
1	Friction	0.357 – 0.757	0.757	(Higher is better)
2	Wear (x10^{-12} mm^3/N-m)	23.98 – 0.727	0.727	(Lower is better)
3	Hardness (S-scale)	83 – 91.5	87.25	(Midpoint)
4	Cold Shear strength(kg/cm^2)	29.5 – 32	32	(Higher is better)
5	Porosity (%)	6.1 – 6.9	6.1	(Lower is better)
6	Thermal conductivity (W/(m K))	1.7 – 2.22	2.22	(Higher is better)
7	Heat swell at 200°C (mm)	0.045 – 0.070	0.045	(Lower is better)
8	Loss of Ignition at 850 °C (%)	11.06 – 12.88	11.06	(Lower is better)
9	Acetone extraction (%)	0.32 – 0.57	0.32	(Lower is better)

Table 8. The model calculation of the dependent degree of sample S1.

Parametres x_i	Interval x_i	Optimum point M_i	Measured Sample Value x_i	Dependent degree $K(x_i)$	Weight x_i	Mean of $\overline{K(x_i)}$
1	[0.357, 0.757]	0.757	0.473	0.307	1/9	0.2395
2	[23.98, 0.727]	0.727	13.29	0.459	1/9	
3	[83, 91.5]	87.25	83	0	1/9	
4	[29.5, 32]	32	29.5	0	1/9	
5	[6.1, 6.9]	6.1	6.1	0	1/9	
6	[1.7, 2.22]	2.22	1.7	0	1/9	
7	[0.045, 0.070]	0.045	0.07	1	1/9	
8	[11.06, 12.88]	11.06	11.06	0	1/9	
9	[0.32, 0.57]	0.32	0.41	0.39	1/9	

Table 9. Dependent degree, weighed dependent degree and ranks of the brake pads.

Dependent degree	S1	S2	S3
$K(x_1)$	0.307	0.392	0.451
$K(x_2)$	0.459	0.6423	0.6216
$K(x_3)$	0	0.941	0.941
$K(x_4)$	0	1	0.6
$K(x_5)$	0	1	0.125
$K(x_6)$	0	0.6923	1
$K(x_7)$	1	0	0.28
$K(x_8)$	0	0.6813	1
$K(x_9)$	0.39	0	1
$\overline{K(x_i)}$	0.2395	0.5943	0.6687
Rank	3	2	1

4. CONCLUSION

The following points were inferred from this study.

1. At high speeds, the average coefficient of friction (Avg μ) for low Cu content (S1) and medium Cu content (S3) are unstable. Hence, it is reconfirmed that Cu presence paves way for friction films to stabilize μ.
2. For less Cu content (S1), the thermal conductivity is very less and so heat accumulates at the film which disturbs the contact between brake pad and the disc and hence material gets worn out easily.
3. The physico-mechanical performances of the brake pads are satisfied with the OEM standards.
4. Sample S3 with 80 % Cu and 20 % Zn combination proves to be a better performer based on the extension evaluation method.
5. The overall performance of the brake pads from best to worst based on extension evaluation method as follows: S3, S2, and S1.

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