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Abstract: Since 1925, asbestos brake pads have been widely used due to their variety of benefits over the other materials. Use of Copper was also considered as crucial in the production of friction material. Due to adverse effects on the human health and environment, use of Asbestos has been banned and in near future, the use of copper will be restricted as well. India is an agricultural country and being the 2nd largest producer of rice and sugarcane, abundant agricultural waste of rice husk and sugarcane bagasse is available. Majority of the crop residue are burned to manage such huge amount of waste, causing environmental pollution. The objective of this study was to utilize this huge amount of agricultural waste to develop novel Asbestos-free, copper-free brake pad friction material (BFM). The samples have been made by hot compression method by varying the percentage of rice husk (RH) and sugarcane bagasse ash (SCBA) with Phenolic resin as binder. RH has been employed as friction modifier and SCBA as filler. Brass chips were added as one of the substitutes for copper. Two formulations developed have been characterized by physical test, Mechanical tests, experiments on friction test rig, investigation using pin on disc and Thermogravimetric analysis (TGA). It has been observed that both density and hardness were higher for sample 1. The average Coefficient of Friction (COF) for both samples were 0.36 and 0.4 respectively, found to be suitable for automotive brakes. The cumulative wear has been found to be higher for sample 1, in spite of higher hardness. Both samples showed similar behavior and good temperature resistance by retaining 80% of their mass at 600^{O}C in TGA, was the most promising thing.

Keywords: Asbestos free; Copper free; Rice husk; Sugarcane Bagasse; Agricultural waste

1. Introduction

The brake system designs, that are used in vehicles, are of two types: Drum brakes and Disc brakes. Nowadays, most of the vehicles use disc brakes as they dissipate heat in a better manner. Compared to drum brakes, disc brakes have superior fade resistance, self-adjustment capabilities, better cooling, are more resistant to water and dirt, require less maintenance, and have a bigger surface area per unit weight of brake[1)].

The effectiveness of the brake is influenced majorly by the type of friction materials used. The friction material comprises of variety of distinct basic ingredients. The components range from metallic particles or fibers, to mineral, carbon, and lubricating fibers, as well as various abrasives and fillers. All of them are bound together by a polymeric binder, typically a thermosetting polymer[2)]. Nowadays nearly 80% of brake pads used in automobiles are asbestos-free organic type. These pads consist of binder, fibers, abrasive, lubricant, fire-resistant materials, and other reinforcements[3)]. The composition of the ingredients may vary as per application. However, some ingredients are common while making friction material. There are friction materials that can be defined with particular characteristics and used for particular applications.

British Belting and Asbestos Limited (BBA) introduced asbestos-based brake pad material in 1925 because of its capacity to remove excessive heat. Since they had excellent mechanical and tribological qualities, asbestos fibres incorporated in polymeric matrix and other components for brake pads have been utilized for a long time[4)]. Since it was found to be carcinogenic, health organizations banned use of asbestos in brake pad manufacturing[5)]. The use of heavy materials such as copper has been restricted, as it causes aquatic toxicity[6)] (refer Fig. 1).

Replacing copper has been one of the biggest challenges as its effect on brake pad performance is dominant. It is a well-known fact that replacement of copper by a single ingredient is difficult[7]. However, some material like steel and Aluminum fibers, Jute fiber, Natural fiber, Barite, Thermo graphite, Hexagonal boron nitride etc. can be used, in combination, as a replacement for copper[8]. As a substitute, brass can be added in brake pad formulations due to its ability to enhance thermal conductivity, tribo-load bearing capacity, fade resistance, and wear resistance[9]. Some Researches showed that brass fillers in brake pads, act as reinforcing elements, providing primary contact sites and solid lubrication for smooth sliding behaviour[10]. Studies have demonstrated that the composition of brass, particularly the copper-zinc ratio, significantly impacts the tribological and physico-mechanical performance of brake friction materials, with brass containing 80% copper and 20% zinc showing superior performance[11]. Furthermore, the addition of brass particles increases thermal properties and contributes to friction and wear mechanisms, with an optimal quantity of 4.5 wt. % of brass enhancing the stability of the friction coefficient[12]. It has been also noticed that Tribo-performance were best when the brass was at the optimal value of 8%,but drops thereafter[13].Overall, brass plays a vital role in improving the overall performance and effectiveness of brake pads in automotive applications[6].

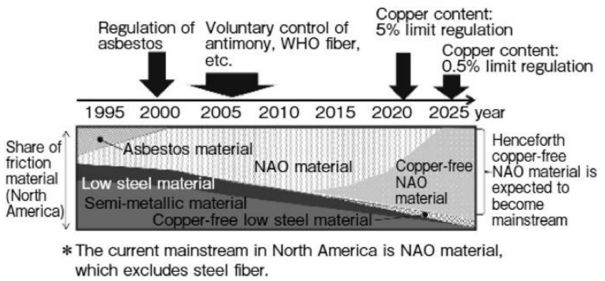


Fig. 1: Change in US regulation of chemical substances for brake pads[7].

India is a farming nation. Approximately 70% of Indians rely on agriculture as their primary source of income. With 1.3 billion people living, India needs a huge quantity of food to meet their nutritional needs[14]. India is the world's second-largest producer of a wide range of commodities, including rice, wheat, sugarcane, and more. Therefore, a significant amount of agricultural waste, including crop residues, is also produced as a result of this enormous production[15,16]. To get rid of this enormous amount of garbage, farmers generally burn agricultural leftovers in an open field. Human health is severely impacted by atmospheric pollution brought on by this residue burning[17]. The exposure to air pollution is the second most significant cause of poor health in South Asia[18]. Exposure to air pollution can cause respiratory, neurological, cardiovascular, and skin and eye discomfort, among other negative effects. Asthma, bronchitis, Chronic Obstructive Pulmonary Disease [COPD], lung capacity loss, emphysema, cancer, and other chronic ailments can be brought on by high air pollution levels[19].

As the globe becomes more environmentally conscious, many industries have started using industrial or agricultural waste for a variety of purposes, such as binding and structural reinforcement, instead of dangerous compounds. Reuse of this waste doesn't damage the environment, when certain materials are added and blended. The high coefficient of friction, low wear at room temperature, and resistance to temperatures as high as 250°C make phenolic composites a popular choice for car brake pads. Organic components can be used in place of hazardous ones when creating ecologically friendly brake pads[20–22].

Manufacturers historically believed that complying with environmental standards will be costly and detrimental to their profit line. Nonetheless, research indicated that successful manufacturers are those who are thought to be more ecologically conscious[23]. There have been various attempts made by researchers to develop non-asbestos friction material using organic and agricultural waste. The materials like Kenaf, Pineapple, Palm kernel shell, Abaca, Hemp, Flax, Bamboo, Coconut (coir), Jute, Ramie, Sisal[24] corn husk[25], Rice husk[26,27] and their derivatives[28] Sugarcane Bagasse[29] etc. were used as an ingredient for making friction material.

Previous studies showed the effects of different natural fibre weight percentages on the mechanical and tribological characteristics of braking pad materials[30,31]. The studies also highlighted the environmental benefits and life-cycle advantages of employing natural fibers in brake pad application[32–34]. Hot compression moulding was dominantly used in many studies. In some cases, BFM was made by hand layup techniques to carry out wear studies using Pin on disc and Taguchi method[35–37]. Studies have also been carried out to improve the wear and frictional properties of asbestos-free friction materials and to comprehend the wear mechanisms of these materials. The brake pad surfaces before and after the actual service was examined to understand the wear modes. To understand more about the physical and chemical alterations on the damaged surface, SEM and EDXS studies has been conducted on the real-service pad[38].

Rice husk is a residual waste product generated when the outer layer of rice grains aggregates during the milling process. The fibrous by-product of crushing sugarcane to release its juice is called bagasse. Bagasse has sufficient potential to be used as boiler fuel in cogeneration facilities and sugar mills, even though its benefits have not yet been fully realized. These leftovers cannot be regarded as waste because they were historically utilized as raw materials for numerous manufacturing processes, fuel sources, and animal feed[39].

Rice husk had been explored as an effective alternative in the manufacturing of brake pads due to environmental concerns associated with traditional materials like asbestos[40]. Research had been looked into adding rice husk ash and teak wood powder to brake pad composites.

The results suggested that these materials have promising mechanical qualities, including hardness, density, wear resistance, and braking distance, and their heat resistance satisfies industry requirements[41]. Additionally, The possible use of silica extracted from rice husk ash as a filler in rubber blends has been investigated, with the aim of improving physico-mechanical characteristics and oil resistance in applications such as fluid sealing[42]. Furthermore, the combination of rice husk with biodegradable polymers had been explored to develop eco-friendly brake pad composites, aiming to achieve wear properties comparable to commercial asbestos-based brake pads[43]. These findings highlighted the potential of utilizing rice husk in brake pad formulations to create an effective alternatives for automotive applications.

The particle size of rice husk plays a critical role in defining the properties of brake pads. Researches had been shown that different particle sizes of rice husk dust (RHD) impact the hardness and impact resistance of automotive brake pads differently. For instance, smaller particle sizes like 80-mesh RHD in a 10% composition can significantly enhance hardness resistance, while larger sizes like 100-mesh RHD in a 30% composition can improve impact resistance by distributing energy over a wider area[44]. The significance of particle size in composite materials had been further demonstrated by the research on rice husk particle sizes in PPVC composites, which shows that different sizes affect density, tensile strength, Young's modulus, and elongation at break[45]. Additionally, the incorporation of rice husk dust in brake pad materials had been found to enhance friction coefficient due to the silica content in rice husk, providing a ceramic-like behavior[46].

Sugarcane bagasse ash (SCBA) has been explored for various applications, including its potential use in brake pads. SCBA, an industrial by-product rich in silica, had shown potential as cost-effective filler in polymer matrices[47]. Typically, brake pads utilize alumina and silica as primary abrasives[48]. By incorporating SCBA into phenolic-based composites for brake pads, researchers aimed to enhance the performance of these essential automotive components. The interaction between SCBA and natural rubber, facilitated by a silane coupling agent, has demonstrated improved mechanical properties in polymer composites. This has been indicating the potential of SCBA to be a valuable reinforcement material in brake pad formulations[49]. This innovative approach not only repurposes a significant industrial waste product but also contributes to environmental protection by reducing landfill disposal of SCBA[50].

Agricultural residues are composed of organic constituents such as cellulose, lignin, fibre, and trace amounts of crude protein and fat. They also comprise a variety of minerals, such as iron oxide, alumina, and silica. Certain plants take in different minerals and silicates from the soil during growth and build those up into structures. Compared to long-lived trees, yearly growing plants have higher quantities of inorganic elements, particularly silicates. Thus, rice, wheat, sunflower, tobacco, and sugarcane are among the plants with a high content of silica. The ash produced by carefully processing the agricultural leftover is interesting because the residue itself cannot be utilized as it is[39,51–53]. Table 1 shows that Rice husk and Sugarcane Bagasse has significant amount of yield (Ash) and silica content in ash, primarily in an amorphous form[39].

In many of the previous studies carried out on organic materials, the particulate matter (PM) emission was not assessed, leads to misleading evaluation of their approach. As stated before, the silica content of natural ingredients such as Rice husk and Sugarcane Bagasse contributes to their unique characteristics. According to the IARC[54], crystalline silica belongs to group 1 of carcinogenic agents and is considered harmful when inhaled repeatedly and on a regular basis. Since amorphous silica is classified in IARC group 3, it cannot be classified as carcinogenic to humans, unlike crystalline silica. Amorphous silica may nevertheless have some negative health impacts, according to certain research[55], however they may not be as severe as those of crystalline silica[28].

Table 1. Ash and silica content of plants[39].

Plant	Parts of the plant	Ash (%)	Silica (%)
Sorghum	Leaf sheath epidermis	12.55	88.7
Wheat	Leaf sheath	10.48	90.56
Corn	Leaf blade	12.15	64.32
Bamboo	Nodes (inner portion)	1.49	57.4
Bagasse	--	14.71	73
Lantana	Leaf and stem	11.24	23.28
Sunflower	Leaf and stem	11.53	25.32
Rice husk	---	22.15	93
Rice Straw	----	14.65	82
Bread fruit tree	Stem	8.64	81.8

Considering all the issues stated in above literature, The main goal of this work was to create eco-friendly non-asbestos friction material utilizing rice husk (RH) and sugarcane bagasse ash (SCBA), taking into account the benefits of both materials on tribological performance. The rice husk was employed as a friction modifier and sugarcane bagasse ash as a filler material in addition to other frequently used materials. Copper is replaced with brass chips and other materials. The binder used in the production of friction materials was phenolic resin. The samples were made by the most popular method of manufacturing i.e., hot compression moulding. The samples were tested for physical, mechanical, tribological characteristics. The thermal degradation of the compositions was tested using TGA.

As mentioned in literature, the burning of residue crops became a threat to environment and humans. The thought has to be given to reuse these agricultural wastes in domestic or industrial applications. This was an attempt to utilise huge waste of rice husk and sugarcane bagasse available in brake pad development. The creation of brake pad friction compound was made possible due to the amorphous silica found in these waste sources.

2. Material Composition

The unground rice husk was obtained from rice mill as a raw material with size of 2-4 mm and sugarcane bagasse ash from vendor. The formulations were made by varying the weight percentage of Rice husk and Sugarcane bagasse ash in the mixture. The sample 1 contain 6% RH and 5% SCBA, whereas sample 2 include 5% RH and 6% SCBA. The remaining constituents has been kept constant. The details of the formulation are as mentioned in Table 2 and 3.

3. Sample preparation

All the ingredients have been weighted on a weighing scale as specified in the composition (refer Table 2). They were mixed in a ball type mixer for 30 min, at a mixer speed of 100 rpm. The samples have been manufactured using standard practices of hot compression moulding. The samples were then cured in furnace. The moulding and curing parameters are given in Table 4.

Table 2. Details of the ingredients of friction material by % weight.

Ingredient	Sample 1 (S1)	Sample 2 (S2)
Alumina	2.00	2.00
Barium Sulfate	22.00	22.00
Brass	2.00	2.00
Calcium Carbonate	9.00	9.00
Carbon powder	1.00	1.00
Coke Powder Grit-40#	3.00	3.00
Friction Dust	9.00	9.00
Glass Fiber (4 mm)	2.00	2.00
Glass Fiber (6mm)	8.00	8.00
Graphite fine (95% purity synthetic)	2.00	2.00
Kaolin or China Clay	2.00	2.00
Magnesium Oxide	2.00	2.00
NBR Powder	1.00	1.00
Phenolic Resins	20.00	20.00
Red oxide	0.20	0.20
Rice Husk	6.00	5.00
Sugarcane bagasse ash	5.00	6.00
Wollastonite	4.00	4.00
Yellow Oxide	0.10	0.10

Table 3. Details of composition in % weight.

Components	Sample 1 (S1)	Sample 2 (S2)
Binders	20.00	20.00
Fillers	58.00	59.00
Friction modifier	12.00	11.00
Fibers	10.00	10.00

Table 4. Manufacturing parameters.

Parameter	Values	
	Sample 1 (S1)	Sample 2 (S2)
Moulding time (min.)	15	15
Moulding Temperature, Average (deg C)	120	120
Moulding Pressure (bar)	350	300
Curing time (min.)	12	12
Curing Temperature (deg C)	100-110	100-110
Curing Pressure (bar)	300	280

As per the studies carried out, it has been found that the density of RH was lesser than SCBA[56,57]. Since sample 1 contain more % of RH, the moulding pressure was more as compared to sample 2. The samples were made into square sheets of 500 x 500 x 10 mm thickness and finished to 7 mm thick using finishing process. Brake pad samples as per the geometry required and pins of diameter 9.5 mm were also cut from the sheet. The specimens thus made are shown in Fig. 2.

Brake pads made with different compositions cannot be utilized until performance tests has been carried out. Various evaluations methods that can be used have been studied in the past[48]. Some of the experimental methods that has been used are discussed in next section.

4. Experimental investigation

4.1 Mechanical and Physical test

The density and hardness of sample 1 and 2 were calculated using the standard procedure as per IS2742/2014 part 3. Maximum force and Compression strength has been calculated by conducting tests as per ASTM D 6641-2023. The rate of grip separation / crosshead speed was 0.05 in/min. The average sample size used was 26.53 mm wide and 5.31mm thick. Tension test were carried out as per ASTM D3039-2014. Ultimate tensile strength and stress at breaking were found out. The rate of grip separation / crosshead speed was 2 mm/min. The preload was 0.1 MPa. The average sample size used was 25.97 mm wide and 5.40 mm thick. Lateral shear strength has been calculated as per ASTM D3518-2018. The force at failure and In-plane shear strength has been found out. The rate of grip separation / crosshead speed was 0.02 in/min. The preload was 0.5 MPa. The average sample size used was 26.72 mm wide and 5.40 mm thick. Flexural test with 3-point bending were carried out as per ASTM D790-2017. Flexural strength and Flexural modulus were found out. The rate of grip separation / crosshead speed was 1% /min. The preload was 0.2 MPa. The average sample size used was 26.01 mm wide and 5.31 mm thick. The span used for the test was 84.8 mm. The results are discussed in following section.

4.2 Experiments on Friction test rig

A friction test rig for disc brake is shown in following Fig. 3(a). It was used for measuring the parameters like coefficient of friction (COF) and temperature at various speeds and loads. The brake pad samples are cut as per the required shape (shown in Fig. 2(a) and (b)) as per the setup specifications. The cut samples were then glued to the back-plate of brake pad using epoxy adhesive (Fig. 3 (b)). The pad has been kept under pressure for 15 min so that the joint attains the full strength. Once the samples were ready, they were placed on the set up for experimentation**.**

The speed was set by variable frequency drive (VFD) and the oil pressure was developed manually using the lever shown in Fig. 3(a). The applied load on cast iron rotor disc (Fig 3(c)) was shown by the display of load cell. The coefficient of friction was calculated from the following equation -

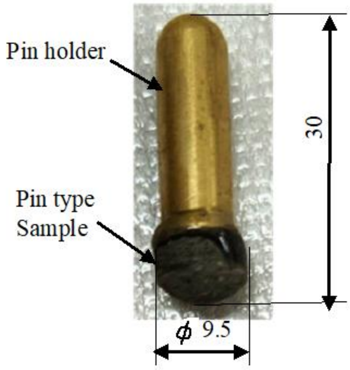
$$T = \mu F R \quad or \quad \mu = \frac{T}{F * R} \quad \ldots\ldots\ldots\ldots\ldots\ldots.. \quad (1)$$

4.3 Investigation on Pin on Disc

To evaluate the tribological behaviour of the samples, DUCOM Pin on disc tribometer was used. The setup is shown in following Fig. 4. The pins of diameter 9.5 mm were cut from a 10 mm thick sheet of each sample 1 and 2. The pins were glued to metal pins as shown in Fig. 2(c).

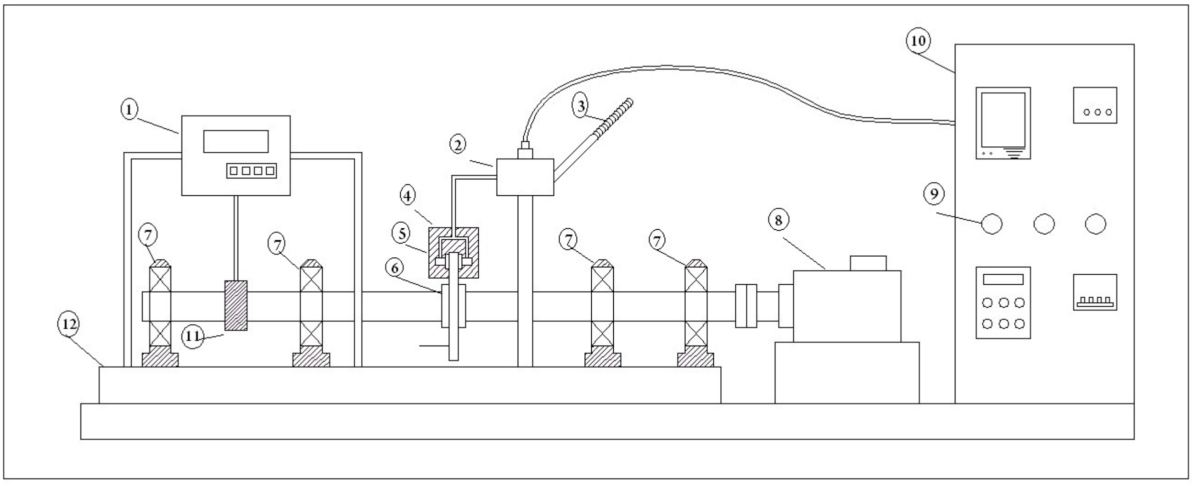
(a)

(b)



(c)

Fig. 2: (a) Sample with 6% RH & 5% SCBA, (b) Sample with 6% SCBA & 5% RH, (c) Pin type samples glued to pin holder.



(a)

1. Load indicator, 2. Oil pumping device, 3. Lever for operating pump, 4. Brake Calliper, 5. Brake pads, 6. Rotor or disc, 7. Bearing, 8. 3.7kW AC Motor, 9. LED, 10. Control Unit (Pressure indicator, speed indicator, VFD control), 11. Load cell, 12. Frame.

(b)

(c)

Fig. 3: (a) Schematic of friction test rig for disc brake, (b) Brake pad, (c) Rotor disc used in setup.

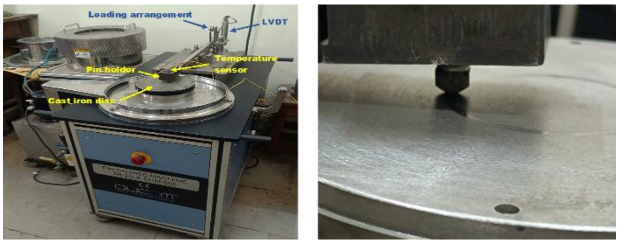


Fig. 4: Pin on disc set up with specimen.

4.4 Thermogravimetric Analysis (TGA)

One of the main causes of poor fading performance in friction materials is frequently the thermal breakdown of the organic constituents. The Constituent materials decompose due to molecular disintegration and chemical reactions at high temperatures. Although 500^{O}C is the more frequent temperature of friction materials in braking systems, it can exceed up to temperatures as high as 800^{O}C[58,59]. The measuring of weight changes that occur when a specimen is heated to a predetermined heating program is known as Thermogravimetry (TG). TG often entails calculating weight loss in relation to temperature. In order to forecast the performance and reaction of the braking system over time, it is therefore essential to identify and gather the temperature-weight-loss profile of the constituent materials and formulations in any attempt to create innovative friction material.

A Universal V4.5A TA Instruments: SDT Q600 V20.9 Build 20 was the analytical tool utilized in this investigation. At a scan rate of 10°C/min, the temperature was ranging from 30^{O}C to 890°C. In a nitrogen atmosphere, a powdered sample weighing at least 10 mg was employed. The weight loss was calculated in 4 different steps of temperature.

5. Results and discussion

The friction materials' characterisation was done using physical, Mechanical, tribological tests and TGA, as discussed below.

5.1 Mechanical and Physical tests

The density and hardness of sample 1 and 2 were calculated as per IS2742/2014 part 3. The results are as shown in Table 5.

The density of commercial brake pad friction material ranges between 1.01 to 2.06 gm/cc[60]. The result showed that both the compositions satisfy the minimum density requirement. Generally, the brake pad material with lower density is preferred as it has less mass and lightweight. The rise in density was due to greater % of filler content. The major cause was increase in filler particle packing, which improve the homogeneity of the composite brake pads. The voids in the mixture between other particles are filled with amorphous silica particles available in SCBA. In addition, other organic contents in RH, viz. hemicellulose, lignin etc. also contribute to rise in density[61].

Table 5. Physical and mechanical test results.

Property	Sample 1	Sample 2
Density (gm/cc)	2.00	1.98
Hardness (HRL)	100	95
Compression strength (MPa)	74.42	58.21
Tensile strength (MPa) at failure	9.18	14.61
In-plane shear strength (MPa) at failure	3.85	6.41
Flexural strength (MPa)	27.91	30.25

The hardness of sample 1 and 2 were calculated as per IS2742/2014 part 3. The results are as shown in Table 5. The hardness range of 70–100 is expected for an ideal mixture of a brake pad friction material[2),62]. The commercially used asbestos based brake pad material has hardness of about 101HRB. The recorded hardness values were well within the range of hardness values required for brake pad material. Although the percentage of phenolic resin was same in both the samples, the hardness of sample 1 is greater than sample 2. This shows the bonding of particles in sample 1 is better.

Other Mechanical tests such a compression test, tension test, In-plane shear test and flexural test were carried out using ASTM standards as mention in earlier section. The results are tabulated in Table 5.

Based on the particular formulation and kind of brake pad, the compressive strength of brake pads reported in literature are usually ranges from 70 to 125 MPa[63,64]. The compressive strength of both samples has been less than the commercial brake pad, but within the range. This is due to larger particle size of rice husk. Compressive strength improves with smaller particle size[45,65]. Out of the two samples, sample 1 has more compressive strength as it was more dense than sample 2. The shear strength of commercial brake pad (asbestos based) material is 5.46 MPa[66]. The shear strength of sample 1 is less than commercial brake pad due to presence of larger weight %

of rice husk. Whereas, in sample 2 the SCBA was larger in weight %, causing a better bond of particles with binder during moulding process. The tensile strength of commercial brake pad is 7.0 MPa[67]. Both samples showed tensile strength at par with commercial brake pad material. The typical range of brake pads' flexural strength as mentioned by various authors is between 10-40 MPa[68]. The precise amount is determined by the manufacturing process, bonding, reinforcements, and material composition. Both samples developed showed the strength within the limits.

5.2 Experiments on Friction test rig

The tests were carried out on friction test rig with disc brake (Fig. 5). The braking loads applied were 2 to 8 kg, at different rotor speeds: 250, 500 and 750 rpm. The speed was restricted to 750 rpm due to vibrations of setup at higher speeds. The maximum friction radius of cast iron rotor was 110 mm. The maximum load recorded by load cell was 10 kg. The coefficient of friction and maximum temperature for each speed and load combination was recorded. Each test has been carried out for a sliding distance of 2000 m.

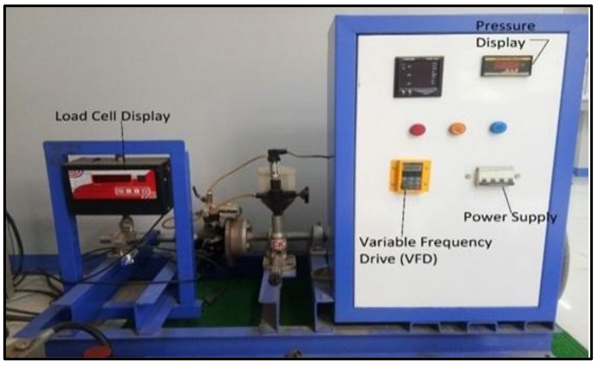


Fig. 5: Friction test rig for friction test.

The brake pad was cooled using fan cooling after every test. Generally, the nominal contact pressure for disc braking is 0.2 - 1.5 MPa[69]. The maximum contact pressure observed during the test was 0.22 MPa. The observations were taken for both the samples, as given in following Table 6.

Table 6. Observations of friction test.

Sample No.	Rotor Speed (RPM)	Brake Load (kg)	COF	Temperature (deg. C)
S1	250	2	0.35	67.6
	250	4	0.47	111.0
	250	6	0.55	121.0
	250	8	0.58	115.0
	500	2	0.30	68.0
	500	4	0.42	147.0
	500	6	0.55	165.0
	500	8	0.68	166.0
	750	2	0.33	75.0
	750	4	0.42	183.0
	750	6	0.61	183.0
	750	8	0.64	159.0
S2	250	2	0.33	55.0
	250	4	0.46	89.0
	250	6	0.52	152.0
	250	8	0.66	145.0
	500	2	0.34	66.3
	500	4	0.43	109.1
	500	6	0.50	165.0
	500	8	0.59	175.1
	750	2	0.47	76.0
	750	4	0.60	128.0
	750	6	0.71	197.0
	750	8	0.69	249.0

As per the data collected from friction test, variations in coefficient of friction for different combinations of rotor speeds and braking loads for both the samples are shown in Fig. 6. The COF was calculated as per equation 1 mentioned in earlier section.

The coefficient of friction was found to be varying between 0.3 and 0.68 for different loads and speeds. The average COF for sample 1 and 2 was found to be 0.49 and 0.52 respectively. The variations in COF for sample 1 was minimum at a given load and speed. In all the cases, it has been noted that the COF of sample 2 was higher than sample 1 at higher speeds for all the braking loads applied. Since the moulding pressure of sample 1 was more, the particles of sample 1 have been closely spaced than sample 2 and have greater contact during braking. Generally, as the moulding pressure increases, average COF also increases[70]. But it is not true for all the materials. In this study, COF of sample 1 was observed to be smaller than sample 2. It has been also noted that COF increases with temperature of pad. This was due to enlarging the contact. area of pad as a result of thermal deformation.

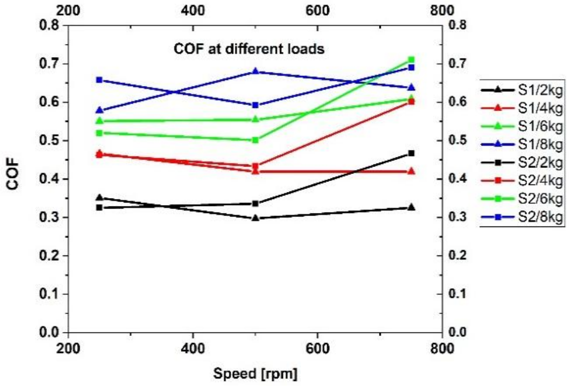


Fig. 6: COF vs. rotor speed at different braking loads for sample 1 and 2.

The variations in pad temperature for sample 1 and 2 with respect to different speeds and braking loads has been shown in following Fig. 7.

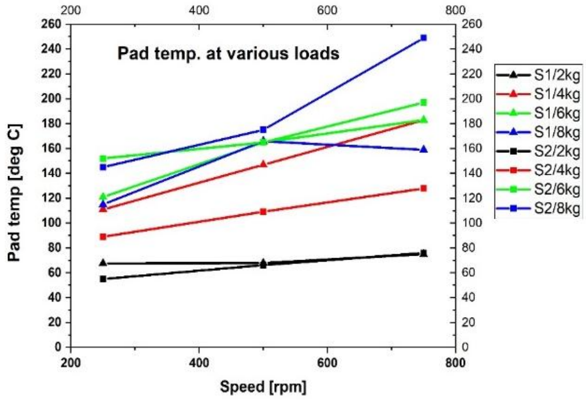


Fig. 7: Pad temperature vs. rotor speed for sample 1 and 2 at different braking loads.

It has been observed that the temperature varies between 50^{O}C to 260^{O}C. The Temperature of sample 2 increased drastically with the braking load. The graph shows that the temperature gradient of sample 1 is flatter than sample 2. It has been observed that the temperature varies almost linearly with speed for all the braking loads applied. Since the maximum braking load that can be measured on test rig is 10 kg, the variation in temperature for higher loads could not be estimated.

5.3 Pin on disc experiment

Pin on disc experiment conducted on Ducom make pin on disc machine as per ASTM G99-2017[71]. The machine was equipped with a data acquisition system and Winducom 2010 software. Brake discs are generally made up of grey cast iron[72]. So, cast iron disc of 8 mm thickness and 162 mm diameter was ~~is~~ used for the experiments. The hardness value of the disc was 103HB (57 HRC).

The experiment was carried out at normal atmospheric conditions. The test parameters are given in Table 7[29),71),73]. The variations in COF for both samples at a given load and speed are shown in following Fig. 8(a) and (b).

Table 7. Test parameters for pin on disc experiment.

Parameter	Values
Applied Load, N	25, 35
Sliding Speed, rpm	500, 750, 1000
Track diameter, mm	60
Sliding Time, minutes	20

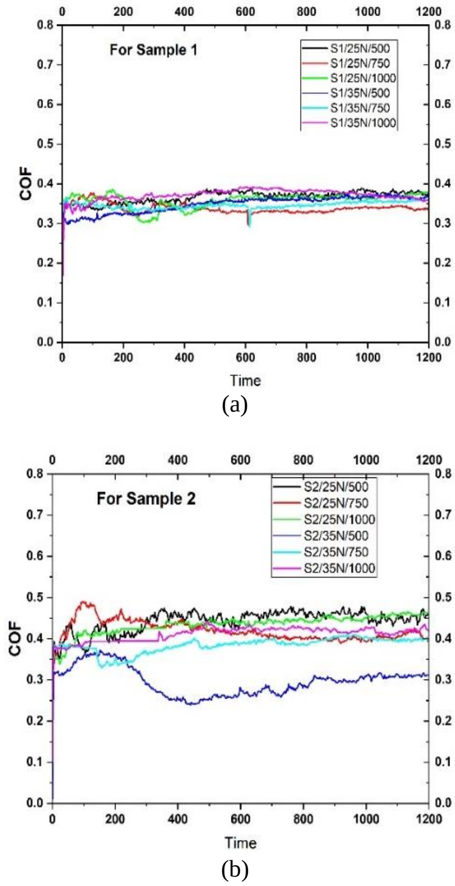


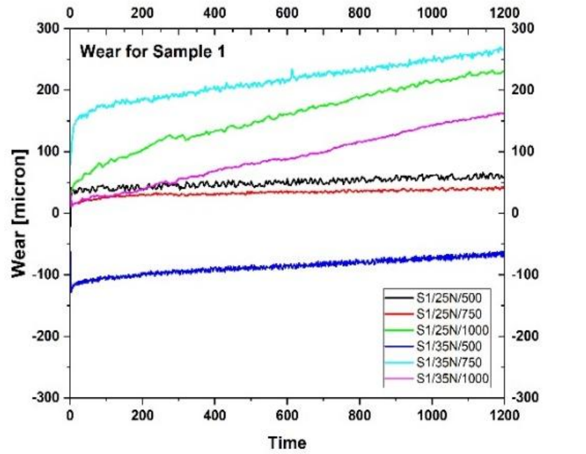
Fig. 8: (a) and (b) COF for sample 1 and 2 at applied load of 25 N and 35 N at sliding speed of 500rpm, 750rpm and 1000 rpm.

Generally, COF value ranges between 0.3 - 0.6 for different Automobile and railway applications[24]. It has been observed that the average COF for sample 1 is less than sample 2 for same operating conditions as shown in Table 7. Similar results were obtained during experiments on friction test rig. The scatter of COF for sample 1 is smaller and the values are lying within the range of 0.3-0.4 for all load and speed combinations. In contrast, COF of sample 2 is more scattered from 0.25-0.5. It can be ascertained that COF of sample 1 is more stable compared to sample 2. The results of Pin on disc are tabulated in following Table 8.

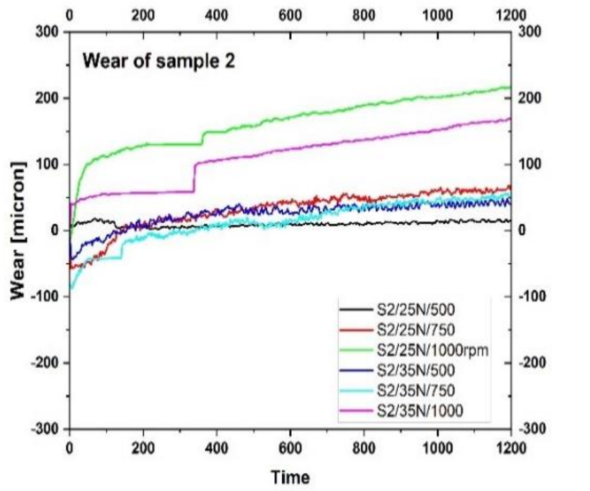
The wear values are recorded from pin on disc experiments and the plots of both samples tested against different load and sliding speeds shown in following Fig 9 (a) and (b). The maximum wear values are recorded after running the experiment for 20 min and shown in following Table 9.

Table 8. COF values for both samples at different loads and speeds.

For Sample 1			For Sample 2		
Load (N)	**Speed (rpm)**	**Avg. COF**	**Load (N)**	**Speed (rpm)**	**Avg. COF**
25	500	0.37	25	500	0.44
25	750	0.34	25	750	0.42
25	1000	0.36	25	1000	0.44
35	500	0.35	35	500	0.30
35	750	0.35	35	750	0.38
35	1000	0.37	35	1000	0.42
Overall Average		0.36	Overall Average		0.40



(a)



(b)

Fig. 9: (a) and (b) Wear of sample 1 and 2 at applied load of 25 N and 35 N at sliding speed of 500rpm, 750rpm and 1000 rpm.

The wear values after 20 min of each test are shown in following Table 9. The results shows that wear is greater for sample 1. As Fig. 9 illustrates, the wear values rise with speed and load. As the sliding speed increases, so does the rate of repetitive impact loading cause by the harsh asperities on the counter-face. This increases the frictional thrust, which causes chattering and localized vibration at the sliding surface, which in turn accelerates the de-bonding and fracture of the reinforcing fibers. Due to their damage to the counter-face film, these fibers may enhance the specimen's wear rate[69].

Table 9. Wear values in microns for both samples at different loads and speeds.

Sample 1			Sample 2		
Load (N)	**Speed (rpm)**	**Wear (micron)**	**Load (N)**	**Speed (rpm)**	**Wear (micron)**
25	500	66.13	25	500	18.15
25	750	43.51	25	750	68.71
25	1000	231.90	25	1000	217.21
35	500	-61.83	35	500	48.79
35	750	269.58	35	750	56.39
35	1000	163.22	35	1000	169.22
	Average	118.75		Average	96.41

5.4 Thermogravimetric analysis

The TGA indicates the weight decomposition at different temperature. The test was carried out and results of tests for both samples are shown in graphical form as shown in following Fig. 10 and 11.

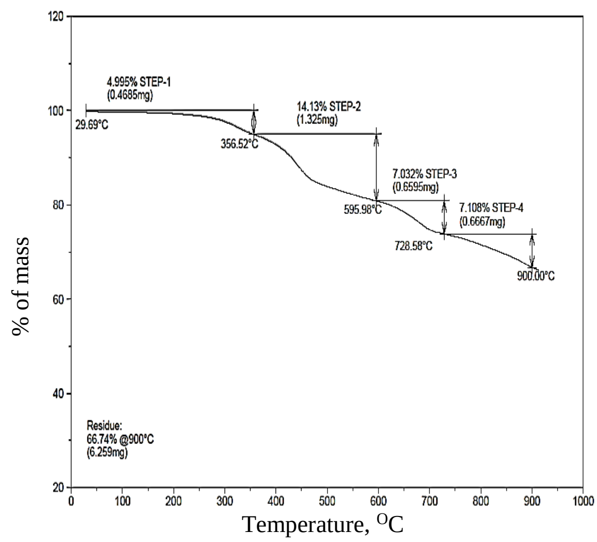


Fig. 10: TGA results of sample 1.

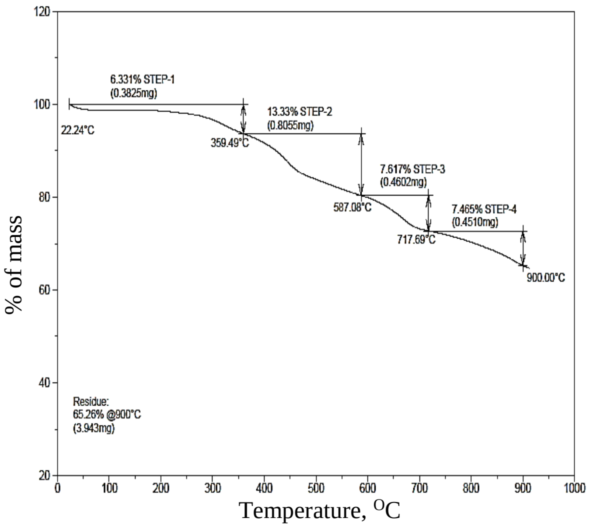


Fig. 11: TGA results of sample 2.

A mass loss of approximately 2% was noticed upto 300^{O}C for S1 and the same was observed to be slightly higher for S2. It is evident that both samples begin to lose mass beyond 300^{O}C, a phenomenon that is related to the thermal degradation of organic components such as RH, rubber and resin[74)]. Up to 890^{O}C carbonaceous matter continues to oxidize and decompose. Between 300^{O}C and 600^{O}C, the TGA showed a higher % loss in mass of S1 than S2. The rate of degradation is almost same for S1 and S2 after 600^{O}C.

The formulation S1 showed slightly higher weight loss in this range of temperature 300^{O}C – 600^{O}C. The greater the amount of rice husk in the formulation, the greater was the observed thermal degradation. In contrast, S2 has more % of SCBA and hence it can sustain more temperature with lower % loss of mass. Some significant mass loss occurred from 600^{O}C onwards. This corresponds to the range of thermal degradation of calcium carbonate, present in both formulations[75)]. Overall, both formulations showed similar behavior and good temperature resistance, as they retain approximately 80% of their mass at 600^{O}C, which is higher than the range of temperature reached in the adopted brake test procedure (SAE J2522).

6. Conclusions

The investigation of agricultural waste, such as rice husk and sugarcane bagasse ash, in the brake friction material has been done in the present study. Also attempt has been made to eliminate use of copper in friction material. By determining the mechanical, Tribological and Thermal characteristics, the material characterization was done. Following conclusions were drawn -

- To eliminate the adverse effects of copper, the results of this study showed that the copper can be eliminated by using various alternatives like brass, Alumina, graphite.
- The mechanical tests revealed that the results of compression test, tension test, shear test and flexure test are comparable with commercial brake pads and the previous studies.
- The value of COF cited in reference literature for automobile application ranges between 0.3-0.6. The COF values obtained for both the samples has been in the range 0.36 - 0.4 and suits for automobile braking applications. Stability of COF is additional requirement of BFM. The results also showed that COF for sample 1 was found to be more stable over all the loads and speeds used in the test.
- The wear investigation reported that the wear of sample 1 was more, even though the hardness was higher. The amount of RH is more in sample 1 and the wear value increased due to debonding of fibres from base material during the test.
- The amount of brass used was 2% by weight. Since brass stabilize friction, improves thermal conductivity and tribological properties, more % of brass can be added, but it leads to increase in density of friction material [13]
- Regarding thermogravimetric analysis, the thermal degradation was higher for larger % of rice husk in sample 1 within the temperature range of 300–600^{O}C. The most promising thing was that both formulations retained about 80% of their initial mass up to 600 ◦C.
- It has been shown by the results that rice husk and sugarcane bagasse ash can be used in eco-friendly brake pad development. It also can prove to be a promising idea to reuse agricultural wastes in industrial applications.

Nomenclature

T	Braking torque (N-m)
F	Normal force applied for braking on disc (N)
R	Mean friction rotor radius (m)
μ, COF	Coefficient of Friction (--)
gm/cc	Grams per cubic centimeter
HRL	Rockwell hardness scale ‘L’

References

1) H.P. Khairnar, V.M. Phalle, and S.S. Mantha, “Comparative frictional analysis of automobile drum and disc brakes,” Tribol. Ind., 38 (1) 11–23 (2016). http://www.tribology.rs/journals/2016/2016-1/2.pdf
2) K.L. Sundarkrishnaa, “Friction Material Composites,” Springer International Publishing, 171, (2015). doi:10.1007/978-3-319-14069-8.
3) N. Kumar, A. Bharti, H.S. Goyal, and K.K. Patel, “THE evolution of brake friction materials: a review,” Mater. Phys. Mech., 47 (5) 796–815 (2021). doi:10.18149/MPM.4752021_13.

4) G. Gautier Di Confiengo, and M.G. Faga, "Ecological transition in the field of brake pad manufacturing: an overview of the potential green constituents," Sustain., 14 (5) 1-30 (2022). doi:10.3390/su14052508.
5) P. Senthil Kumar, C. Jegadheesan, S. Narasimmabharathi, R. Nithiyarasan, B. Manideep, and A. Pal Singh, "Investigations on tribological behavior of natural fiber hybrid composites for brake friction," Mater. Today Proc., (Article in press) (available online 1st April 2023). doi:10.1016/j.matpr.2023.04.261.
6) G. Straffelini, R. Ciudin, A. Ciotti, and S. Gialanella, "Present knowledge and perspectives on the role of copper in brake materials and related environmental issues: a critical assessment," Environ. Pollut., 207, 211–219 (2015). doi:10.1016/j.envpol.2015.09.024.
7) T. Ito, "Automotive parts for ' environment , safety and comfort performance ,'" Hitachi Chem. Tech. Report., 11 (55) 46–49 (2012). https://www.resonac.com/sites/default/files/2022-12/en_pdf-rd-report-055-55_sou11.pdf (accessed on 18/08/2024)
8) V. Mahale, J. Bijwe, and S. Sinha, "Efforts towards green friction materials," Tribol. Int., 136 196–206 (2019). doi:10.1016/j.triboint.2019.03.049.
9) K. Asrar Ahmed, S. Rasool Mohideen, S.R. Balachandran, and M.A. Sai Balaji, "Varying cu and zn composition in brass and its effect on the fade and recovery behavior of the phenolic-based friction composites," Polym. Compos., 43 (7) 4478–4494 (2022). doi:10.1002/pc.26706.
10) M. Kchaou, A. Sellami, A.R. Abu Bakar, A.R. Mat Lazim, R. Elleuch, and S. Kumar, "Brass fillers in friction composite materials: tribological and brake squeal characterization for suitable effect evaluation," Steel Compos. Struct., 19 (4) 939–952 (2015). doi:10.12989/scs.2015.19.4.939.
11) K.A. Ahmed, S.R. Mohideen, M.A.S. Balaji, and B.S. Rajan, "Tribological performance of brass powder with different copper and zinc content in the brake pad," Tribol. Ind., 42 (2) 177–190 (2020). doi:10.24874/ti.783.10.19.03.
12) A. Sellami, M. Kchaou, R. Kus, J. Fajoui, R. Elleuch, and F. Jaquemin, "Impact of brass contents on thermal, friction and wear properties of brake linings composites," Mech. Ind., 19 (1) 1-9 (2018). doi:10.1051/meca/2016083.
13) J. Bijwe, M. Kumar, P. V. Gurunath, Y. Desplanques, and G. Degallaix, "Optimization of brass contents for best combination of tribo-performance and thermal conductivity of non-asbestos organic (nao) friction composites," Wear, 265 (5–6) 699–712 (2008). doi:10.1016/j.wear.2007.12.016.
14) R. Mathur, and V.K. Srivastava, "Crop Residue Burning: Effects on Environment," in: Energy, Environ. Sustain., Springer Singapore, 127–140, (2019). doi:10.1007/978-981-13-3272-2
15) N. Jain, A. Bhatia, and H. Pathak, "Emission of air pollutants from crop residue burning in india," Aerosol Air Qual. Res., 14 (1) 422–430 (2014). doi:10.4209/aaqr.2013.01.0031.
16) K. Ravindra, T. Singh, and S. Mor, "Emissions of air pollutants from primary crop residue burning in india and their mitigation strategies for cleaner emissions," J. Clean. Prod., 208 261–273 (2019). doi:10.1016/j.jclepro.2018.10.031.
17) A.R. Sharma, S.K. Kharol, K.V.S. Badarinath, and D. Singh, "Impact of agriculture crop residue burning on atmospheric aerosol loading - a study over punjab state, india," Ann. Geophys., 28 (2) 367–379 (2010). doi:10.5194/angeo-28-367-2010.
18) B. Krishna, K. Balakrishnan, A.R. Siddiqui, B.A. Begum, D. Bachani, and M. Brauer, "Tackling the health burden of air pollution in south asia," BMJ, 359 1–5 (2017). doi:10.1136/bmj.j5209.
19) "Scoping study for south asia air pollution," (n.d.). https://assets.publishing.service.gov.uk/media/5cf0f3b0e5274a5eb03386da/TERI_Scoping_Study_final_report_May27_2019.pdf (Accessed on 26/10/2024).
20) M. Duque-Acevedo, L.J. Belmonte-Ureña, F.J. Cortés-García, and F. Camacho-Ferre, "Agricultural waste: review of the evolution, approaches and perspectives on alternative uses," Glob. Ecol. Conserv., 22, 1-23 (2020). doi:10.1016/j.gecco.2020.e00902.
21) B. Praveenkumar, and S. Darius Gnanaraj, "Case studies on the applications of phenolic resin-based composite materials for developing eco-friendly brake pads," J. Inst. Eng. Ser. D, 101 (2) 327–334 (2020). doi:10.1007/s40033-020-00231-4.
22) D.K. Rajak, D.D. Pagar, R. Kumar, and C.I. Pruncu, "Recent progress of reinforcement materials: a comprehensive overview of composite materials," J. Mater. Res. Technol., 8 (6) 6354–6374 (2019). doi:10.1016/j.jmrt.2019.09.068.
23) N. Bhasin, R.N. Kar, and N. Arora, "Green disclosure practices in india: a study of select companies," Evergreen, 2 (2) 5–13 (2015). doi:10.5109/1544075.
24) A.P. Irawan, D.F. Fitriyana, C. Tezara, J.P. Siregar, D. Laksmidewi, G.D. Baskara, M.Z. Abdullah, R. Junid, A.E. Hadi, M.H.M. Hamdan, and N. Najid, "Overview of the important factors influencing the performance of eco-friendly brake pads," Polymers, 14 (6) 1-22 (2022). doi:10.3390/polym14061180.
25) W. Asotah, and A. Adeleke, "Development of asbestos free brake pads using corn husks," Leonardo Electron. J. Pract. Technol., 7 (31) 129–144 (2017). https://www.researchgate.net/publication/352056082 (Accessed on 18/08/2024).
26) G.S. Gehlen, P.D. Neis, L.Y. Barros, J.C. Poletto, N.F. Ferreira, and S.C. Amico, "Tribological performance of eco-friendly friction materials with

rice husk," Wear, 500–501 (2022). doi:10.1016/j.wear.2022.204374.

27) A.P.G. Nogueira, G. da Silva Gehlen, P.D. Neis, N.F. Ferreira, S. Gialanella, and G. Straffelini, "Rice husk as a natural ingredient for brake friction material: a pin-on-disc investigation," Wear, 494–495 (2022). doi:10.1016/j.wear.2022.204272.
28) D. Carlevaris, M. Leonardi, G. Straffelini, and S. Gialanella, "Design of a friction material for brake pads based on rice husk and its derivatives," Wear, 526–527 (2023). doi:10.1016/j.wear.2023.204893.
29) J. Chandradass, M. Amutha Surabhi, P. Baskara Sethupathi, and P. Jawahar, "Development of low cost brake pad material using asbestos free sugarcane bagasse ash hybrid composites," in: Mater. Today Proc., Elsevier Ltd, 45 (7) 7050 – 7057 (2021). doi:10.1016/j.matpr.2021.01.877.
30) H. Sosiati, Y.A. Shofie, and A.W. Nugroho, "Tensile properties of kenaf/e-glass reinforced hybrid polypropylene (pp) composites with different fiber loading," Evergreen, 5 (2) 1–5 (2018). doi:10.5109/1936210.
31) B. ÖZtüRk, F. Arslan, and S. Öztürk, "Effects of different kinds of fibers on mechanical and tribological properties of brake friction materials," Tribol. Trans., 56 (4) 536–545 (2013). doi:10.1080/10402004.2013.767399.
32) A. Mahyudin, S. Arief, H. Abral, Emriadi, M. Muldarisnur, and M.P. Artika, "Mechanical properties and biodegradability of areca nut fiber-reinforced polymer blend composites," Evergreen, 7 (3) 366–372 (2020). doi:10.5109/4068618.
33) J. Maulana, H. Suryanto, Aminnudin, and J.S. Binoj, "Addition of graphene on the bacterial cellulose nanocomposite membrane with copper oxide reinforcement," Evergreen, 11 (1) 186–194 (2024). doi:10.5109/7172255.
34) Z. Ammar, H. Ibrahim, M. Adly, I. Sarris, and S. Mehanny, "Influence of natural fiber content on the frictional material of brake pads—a review," J. Compos. Sci., 7 (2) (2023). doi:10.3390/jcs7020072.
35) N.M. Mathur, Yashpal, and B. Pratap, "Ascertaining tribological properties of pla matrix composites reinforced with scb/cf fiber with anova and regression analysis," Evergreen, 11 (1) 234–241 (2024). doi:10.5109/7172260.
36) B.S. Rana, G. Bhushan, and P. Chandna, "The impact of nano fly ash particulates on tribological performance of jute /cotton fiber reinforced hybrid bio-composite," Evergreen, 10 (3) 1349–1356 (2023). doi:10.5109/7151682.
37) A. Kumar, and S. Singh, "Fabrication and optimization of wear behaviour of citrus limetta peel particulate composite using hybrid taguchi-gra-pca," Evergreen, 10 (3) 1323–1329 (2023). doi:10.5109/7151679.
38) N. Elzayady, and R. Elsoeudy, "Microstructure and wear mechanisms investigation on the brake pad," J. Mater. Res. Technol., 11 2314–2335 (2021). doi:10.1016/j.jmrt.2021.02.045.
39) R.N. Swamy, "Cement Replacement Materials (Concrete Technology and Design)," Surrey University Press London UK, (1986).
40) A.P. Irawan, D.F. Fitriyana, J.P. Siregar, T. Cionita, P.T. Anggarina, D.W. Utama, T. Rihayat, R. Rusiyanto, S. Dimyati, M.B. Aripin, R. Ismail, A.P. Bayuseno, G.D. Baskara, M. Khafidh, F.P. Putera, and R. Yotenka, "Influence of varying concentrations of epoxy, rice husk, Al2o3, and Fe2o3 on the properties of brake friction materials prepared using hand layup method," Polymers, 15 (12) 1-19 (2023). doi:10.3390/polym15122597.
41) M.A. Kurniawan, Y. Prasetiyo, S. Srianto, A.E. Fahmadi, and R. Rifano, "Characterization of brake pads by variation in composition of teak wood powder and rice husk ash," RSF Conf. Ser. Eng. Technol., 2 (2) 190–197 (2022). doi:10.31098/cset.v2i2.572.
42) H.G.I.M. Wijesinghe, T.N.B. Etampawala, D.G. Edirisinghe, G.R.V.S. Gamlath, R.R.W.M.U.G.K. Wadugodapitiya, and T.A.R.W.M.M.C.G. Bandara, "Properties of rice husk ash silica filled natural rubber and acrylonitrile-butadiene rubber blends," J. Agric. Sci. - Sri Lanka, 17 (1) 1–18 (2022). doi:10.4038/JAS.V17I1.9608.
43) W.E. Primaningtyas, R.R. Sakura, Suheni, I. Syafi'I, and A.A.G.A.D. Adhyaksa, "Asbestos-free Brake Pad Using Composite Polymer Strengthened with Rice Husk Powder," in: IOP Conf. Ser. Mater. Sci. Eng., Institute of Physics Publishing, 462, 1-7 (2019). doi:10.1088/1757-899X/462/1/012015.
44) S.A. Bahari, K.H. Isa, M.A. Kassim, Z. Mohamed, and E.A. Othman, "Investigation on hardness and impact resistance of automotive brake pad composed with rice husk dust," in: AIP Conf. Proc., 1455, 155–161 (2012). doi:10.1063/1.4732485.
45) A.R. Farah Nordyana, A.Z. Romli, and M.H. Abidin, "Effect of rice husk particle size on tensile and density of recycled PPVC composite," in: Adv. Mater. Res., 812, 145-150 (2013). doi:10.4028/www.scientific.net/AMR.812.145.
46) I. Sugözü, "Investigation of using rice husk dust and ulexite in automotive brake pads," Mater. Test., 57 (10) 877–882 (2015). doi:https://doi.org/10.3139/120.110792.
47) N. S. Seroka, R. Taziwa, and L. Khotseng, "Sugar Cane Bagasse Ash: An Agricultural Residue with Potential Rubber Filler Applications," in: Appl. Charact. Rubber Mater., IntechOpen, (2023). doi:10.5772/intechopen.108020.
48) S. Choosri, N. Sombatsompop, E. Wimolmala, and S. Thongsang, "Potential use of fly ash and bagasse ash as secondary abrasives in phenolic composites for

eco-friendly brake pads applications," Proc. Inst. Mech. Eng. Part D J. Automob. Eng., 233 (5) 1296–1305 (2019). doi:10.1177/0954407018772240.

49) G. Barrera Torres, G. Dognani, D.L. da Silva Agostini, R.J. dos Santos, F. Camargo Cabrera, C.M. Gutierrez Aguilar, F.F.G. de Paiva, S. Rainho Teixeira, and A.E. Job, "Potential eco-friendly application of sugarcane bagasse ash in the rubber industry," Waste and Biomass Valorization, 12 (8) 4599–4613 (2021). doi:10.1007/s12649-020-01309-6.
50) S. Deepika, G. Anand, A. Bahurudeen, and M. Santhanam, "Construction products with sugarcane bagasse ash binder," J. Mater. Civ. Eng., 29 (10) 1-10 (2017). doi:10.1061/(asce)mt.1943-5533.0001999.
51) V.V. Matichenkov, and G.S. Snyder, "The method for determination of plant-available silica in soil," Agrochemistry, 1 76–84 (1997).
52) V. V. Matichenkov, E.A. Bocharnikova, D. V. Calvert, and G.H. Snyder, "Comparison study of soil silicon status in sandy soils of south florida," Annu. Proc. Soil Crop Sci. Soc. Florida, 59 (59) 132–137 (2000).
53) N.I. Bazilevich, "The biological productivity of North Eurasian ecosystems," (1993).
54) International Agency for Research on Cancer, "Agents classified by the iarc monographs," (2012). https://monographs.iarc.who.int/wp-content/uploads/2018/09/ClassificationsAlphaOrder.pdf (Accessed on 18/08/2024)
55) R. Merget, T. Bauer, H. Küpper, S. Philippou, H. Bauer, R. Breitstadt, and T. Bruening, "Health hazards due to the inhalation of amorphous silica," Arch. Toxicol., 75 (11) 625–634 (2002). doi:10.1007/s002040100266.
56) Y. Zhang, A.E. Ghaly, and B. Li, "Physical properties of rice residues as affected by variety and climatic and cultivation onditions in three continents," Am. J. Appl. Sci., 9 (11) 1757–1768 (2013). doi:10.3844/ajassp.2012.1757.1768.
57) S.A. Mangi, N. Jamaluddin, M.H. Wan Ibrahim, A.H. Abdullah, A.S.M. Abdul Awal, S. Sohu, and N. Ali, "Utilization of sugarcane bagasse ash in concrete as partial replacement of cement," in: IOP Conf. Ser. Mater. Sci. Eng., Institute of Physics Publishing, 271 1-9 (2017). doi:10.1088/1757-899X/271/1/012001.
58) P. Nawangsari, Jamasri, and H.S.B. Rochardjo, "Effect of Phenolic Resin on Density, Porosity, Hardness, Thermal Stability, and Friction Performance as A Binder in Non-Asbestos Organic Brake Pad," in: IOP Conf. Ser. Mater. Sci. Eng., Institute of Physics Publishing, 547, 1-9 (2019). doi:10.1088/1757-899X/547/1/012012.
59) G. Cueva, A. Sinatora, W.L. Guesser, and A.P. Tschiptschin, "Wear resistance of cast irons used in brake disc rotors," Wear, 255 (7–12) 1256–1260 (2003). doi:10.1016/S0043-1648(03)00146-7.
60) G. AKINCIOĞLU, S. AKINCIOĞLU, H. ÖKTEM, and İ. UYGUR, "Brake pad performance characteristic assessment methods," Int. J. Automot. Sci. Technol., 5 (1) 67–78 (2021). doi:10.30939/ijastech..848266.
61) J. Abutu, S.A. Lawal, M.B. Ndaliman, R.A. Lafia-Araga, O. Adedipe, and I.A. Choudhury, "Production and characterization of brake pad developed from coconut shell reinforcement material using central composite design," SN Appl. Sci., 1, 82 (2019). doi:10.1007/s42452-018-0084-x.
62) ASTM International, "Standard Test Method for Rockwell Hardness of Plastics and Electrical Insulating, ASTM D785-23", (2023).
63) N.A. Hooton, "Metal-ceramic composites in high-energy friction applications," Bend Tech J., 55–61 (1969).
64) A.R. Marewad DS, Singh, GP, "Asbestos free brake pad using micro cellulose fibre for automotive industry," Int. J. Adv. Res. Ideas Innov. Technol., 4 (4) 685–690 (2018). https://www.ijariit.com/manuscripts/v4i4/V4I4-1390.pdf (Accessed on 08/12/2024)
65) V. S. AIGBODION., U. AKADIKE, S.B. HASSAN, F. ASUKE, and J.O. AGUNSOYE, "Development of asbestos-free brake pad using bagasse," Tribol. Ind., 32 (1) 12-18 (2010). http://www.tribology.rs/journals/2010/2010-1.html(accessed on 31/7/2024)
66) A.O.A. Ibhadode, and I.M. Dagwa, "Development of asbestos-free friction lining material from palm kernel shell," J. Brazilian Soc. Mech. Sci. Eng., 30 (2) 166–173 (2008). doi:10.1590/S1678-58782008000200010.
67) I. Olabisi, "Development of asbestos-free automotive brake pad using ternary agro-waste fillers," 3 (7) 5307-5323 (2016).
68) M.N. Joshi, "Disc brake linings-analytical study and selection criteria," in: SAE Tech. Pap. Series, 800782 (1980). doi:10.4271/800782.
69) G. Straffelini, "Friction and Wear: Methodologies for Design and Control," Spinger, (2015). http://link.springer.com/10.1007/978-3-319-05894-8.
70) R. Ertan, and N. Yavuz, "An experimental study on the effects of manufacturing parameters on the tribological properties of brake lining materials," Wear, 268 (11–12) 1524–1532 (2010). doi:10.1016/j.wear.2010.02.026.
71) International ASTM, "Astm g99," Int. ASTM, 05 (2016) 5–10 (2017). doi:10.1520/G0099-17.Copyright.
72) A. Borawski, "Conventional and unconventional materials used in the production of brake pads - review," Sci. Eng. Compos. Mater., 27 (1) 374–396 (2020). doi:10.1515/secm-2020-0041.
73) M.P. Kshirsagar, and H.P. Khairnar, "Comparison of the theoretical and experimental coefficient of

friction for the brake disc-brake pad system," Tribol. Mater., 2 (2) 78–87 (2023). doi:10.46793/tribomat.2023.009.
74) R. Yun, P. Filip, and Y. Lu, "Performance and evaluation of eco-friendly brake friction materials," Tribol. Int., 43 (11) 2010–2019 (2010). doi:10.1016/j.triboint.2010.05.001.
75) X.G. Li, Y. Lv, B.G. Ma, W.Q. Wang, and S.W. Jian, "Decomposition kinetic characteristics of calcium carbonate containing organic acids by tga," Arab. J. Chem., 10 S2534–S2538 (2017). doi:10.1016/j.arabjc.2013.09.026.