Journal of Ocean, Mechanical and Aerospace
-Science and Engineering-
30th March 2024. Vol.68 No.1

March 30, 2024

Potential Optimization of Industrial Waste as an Alternative Material for Composite Filler in Brake Pad Manufacturing – A Review

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Paper History

Received: 16-December-2023
Received in revised form: 25-March-2024
Accepted: 30-March-2024

ABSTRACT

This study investigates the sustainable utilization of fly ash, palm slag and Cement By-Pass Dust (CBPD) waste as alternative materials for environmentally friendly brake pad development. These waste materials, with compositions similar to Asbestos, historically used in brake pad composites, present an eco-conscious solution. Integrating industrial waste in brake pad production offers substantial environmental benefits, technological progress, and commercial advantages. The compaction value and particle size distribution significantly impact brake pad mechanical properties. Adjusting these factors is crucial for meeting desired mechanical property requirements. A large particle size distribution enhances material density and hardness poses challenges in maintaining performance stability at high temperatures despite good recovery values. This paper highlights the potential of waste materials for sustainable brake pad development and underscores the need for careful optimization for high-temperature stability.

KEYWORDS: *Brake pad, Waste management, Industrial waste, fly ash, Cement waste, Palm slag, Non-asbestos composite.*

1.0 INTRODUCTION

Brake pads are one of the components that play a crucial role in the vehicle braking system. They function to slow down and stop the vehicle by converting kinetic energy into heat through friction or heat absorption into the surrounding environment (Adetunji, et al., 2022) [1]. Brake pads, under ideal conditions, must meet several required quality standards, including corrosion resistance, high and stable friction coefficient, lightweight, wear resistance, low noise levels, fade resistance, quick recovery, and economical maintenance costs (Kchaou, et al., 2018) [2], Sun, et al., 2018) [3]. To achieve these quality standards, brake pad materials are designed as composite materials composed of 10-15 different materials (Liu, et al., 2019 [4], Singh, et al., 2017) [5]. According to (Nicholson, 1995) [6] brake pad materials are categorized into four main parts with their respective functions: binders, friction modifiers (abrasives and solid lubricants), reinforcement, and fillers.

The filler material in brake pad composites plays a crucial role in reducing manufacturing costs and modifying friction performance, such as fade resistance, abrasion resistance, and stabilizing the friction coefficient (Sugözü & Dağhan, 2016) [7]. Filler materials in brake pad composites are classified into two types: organic fillers and inorganic fillers. Organic fillers are derived from nature or organic materials (plants or animals). Commonly used organic fillers for brake pads include cashew dust/friction dust and rubber dust. These materials can reduce brake noise (Handa & Kato, 1996) [8], (Singaravelu, et al., 2019) [9] and decrease fluctuations in the friction coefficient at high temperatures (Nawangsari & Rochardjo, 2019) [10]. Agricultural waste products, such as cocoa bean shells, corn husks, rice husks, peanut shells, and palm fiber, have been studied as brake pad fillers (Ubani & Adejare, 2022) [11].

Inorganic fillers are materials derived from minerals. Inorganic filler materials for brake pad composites include barium sulfate ($BaSO4$), mica, vermiculite, and calcium carbonate ($CaCO3$). $BaSO4$ is the most widely used filler for brake pads due to its low cost and non-hazardous nature. $BaSO4$ is utilized as a filler to reduce production costs and improve friction stability during fading cycles (Handa & Kato,, 1996) [8], (Sugözü & Dağhan, 2016) [7]. Calcium carbonate is an alternative inorganic filler to replace barium sulfate, providing thermal stability to brake pads and enhancing fading performance during braking. Meanwhile, mica and vermiculite serve as alternative fillers for brake pads, damping noise during braking and resisting wear at high temperatures (Chan & Stachowiak, 2004) [12].

The current focus in the development of brake pad filler materials is on utilizing agricultural and industrial waste. These waste are repurposed to control/preserve the environment, create solutions for sustainable and eco-friendly materials, and provide added economic value. The use of industrial waste as brake pad fillers is an effective step in replacing filler materials derived from non-renewable natural resources. Research has been conducted to evaluate the potential of by-products and industrial waste as brake pad fillers, including palm slag, fly ash, and cement bypass dust.

2.0 INDUSTRIAL WASTE

2.1 Palm Slag

Palm slag is an industrial waste generated during the oil extraction process from palm oil through incineration. Table 1 illustrates several studies that utilize palm slag waste as a filler material for brake pads. The research conducted has involved varying the composition of palm slag. The consideration for utilizing palm slag waste as a material filler for brake pads is due to its content of both metallic and non-metallic compounds, such as CaO, Fe_2O_3, SiO_2, K_2O, and others, as presented in Table 2 (Ruzaidi, et al., 2013) [13]. These palm slag compounds are found in the constituents of commercial brake pads, suggesting that palm slag waste holds the potential to be utilized as the material filler for brake pads.

The results of thermal analysis TG/DTA, as presented in Figure 1, indicate that palm slag exhibits high thermal resistance due to the absence of significant weight loss with an increase in temperature from 50 to 1000 °C. An increase in weight occurs at temperatures ranging from 500 to 1000 °C due to phase changes (Ruzaidi, et al., 2011) [14].

Tabel 1: Results of palm slag waste research as composite brake pad

Author	**Ruzaidi-Gazali, et al. (2012) [15]**	**Ruzaidi-Gazali, et al. (2013) [13]**	**Ruzaidi-Gazali, et al. (2013) [13]**	**Khoni, et al, 2018 [17]**	**Khoni, et al. (2018) [17]**	**Ruzaidi-Gazali, et al. (2020) [18]**	**Ruzaidi_ Gazali, et al. (2020) [18]**
Optimum Formulation (wt%)	Palm Slag (40), Phenolic Resin (20)	Calcium Carbonate (40), Phenolic Resin (20)	Dolomit (40), Phenolic Resin (20)	Palm Slag (40), Phenolic Resin (20)	Palm Slag (30), Tire Dust (10), Phenolic Resin (20)	Palm Slag (30), Tire Dust (10), Polyester (20)	Palm Slag (40), Polyester (20)
Ingredients Formulation (wt%)	Graphite (10), Steel Fiber (20), Alumina (10)	Graphite (10), Steel Fiber (20), Alumina (10)	Graphite (10), Steel Fiber (20), Alumina (10)	Graphite (10), Steel Fiber (20), Alumina (10)	Graphite (10), Steel Fiber (20), Alumina (10)	Graphite (10), Steel Fiber (20), Alumina (10)	Graphite (10), Steel Fiber (20), Alumina (10)
Manufacturing Process	Hot press 15-17 mpa & Cured 150°C, 5 min, Pressure 10, 20, 40, and 60 Ton	Hot press 15-17 Mpa, Cured 150°C, 5 min, Pressure 10, 20, 40, and 60 Ton	Hot Press 15-17 Mpa, Cured 150°C, 5 min, Pressure 10, 20, 40, and 60 Ton	Hot Press 30 Mpa 150°C,	Hot Press 30 Mpa 150°C,	Hot Press 32.5 Mpa 175°C, 10 min	Hot Press 32.5 Mpa, 175°C, 10 min,
Post Cured	150°C Constant 4 hours	150°C Constant 4 hours	150°C Constant 4 hours	Na	Na	NA	NA
Variable Optimum	Compression Load 60t	Compression Load 60t	Compression Load 60t	Particle Size 600 µm	Particle Size 600 µm	Particle Size 600 µm	-
Particle Size (µm)	600	600	600	600	600	600	600
Density (g/cm3)	2.02	2.17	2.21	**2.25**	**2.22**	NA	NA
Porosity	NA	NA	NA	**37.97**	**35.98**	NA	NA
Wear rate (m^3/m x 10^{-13})	8.9	6	12.2	8.5	4	5.2	6.9
Wear Volume (cm^3 x 10^{-3})	0.89	0.6	1.22	0.85	0.4	0.52	0.69
Coefficient Of Friction (COF)	NA	NA	NA	NA	NA	NA	Na
Hardness (Rockwell E)	61	78	80	55	50	87	**97.6**
Compressive strength (Mpa)	57	53	56	160	145	NA	NA

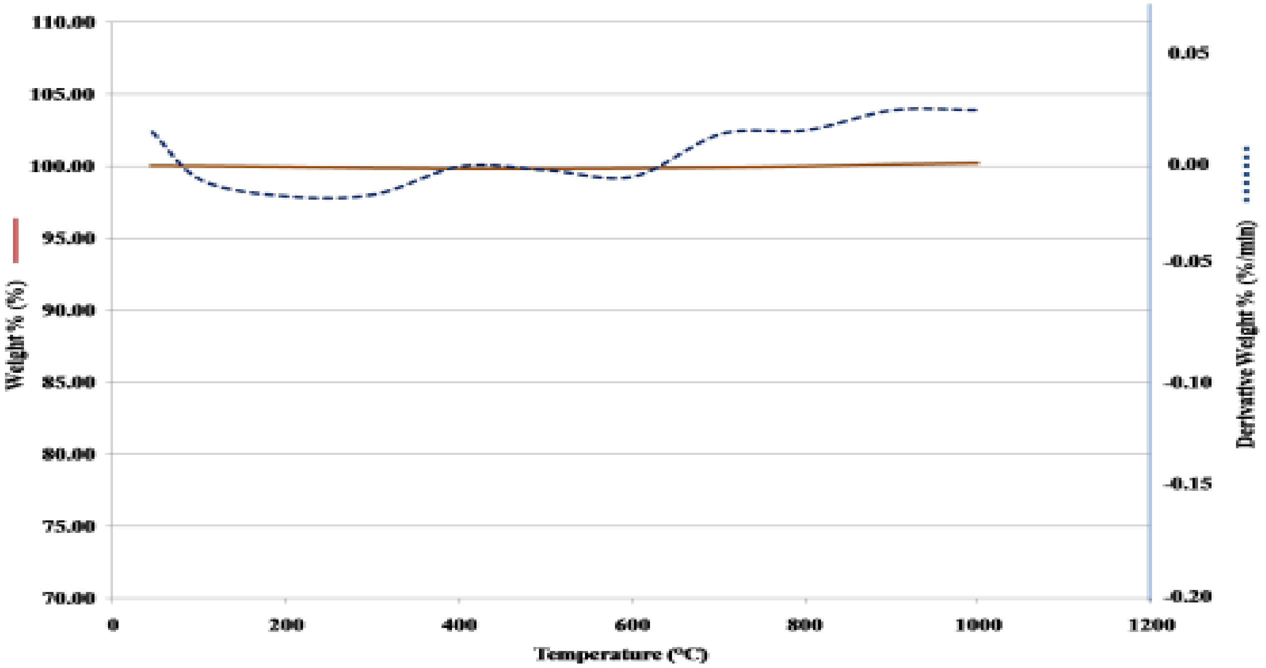

Figure 1: Results of TG/DTA testing on palm slag

Table 2: The chemical composition of palm slag waste by XRF method (Ruzaidi-Gazali, et al., 2011) [14]

Major oxide composition	(wt.%)
CaO	20.4
SiO_2	22.0
Fe_2O_3	29.3
Ti_2O_2	2.11
Ni_2O	0.13
K_2O	23.8
SO_3	12.8
CuO	0.38
Cr_2O_3	0.39
MnO_2	0.58
SrO	0.33
Rb_2O	0.39

Table 3: Mechanical testing results of several filler samples (Ruzaidi-Gazali, et al., 2013) [13]

Sample	Density (g/cm^3)	Volume Wear (cm^3 x 10 $^{-3}$)	Wear Specific (m^3/m x 10^{-13})
Palm slag	2.02	0.89	8.9
Calcium carbonate ($CaCO_3$)	2.17	0.60	6.0
Dolomit	2.21	1.22	12.2
Asbestos (Chand, et al., 2004) [16]	1.89	0.72	7.2

In a study conducted by (Ruzaidi-Gazali, et al., 2012) [15] palm slag was investigated as a filler for brake pads. Palm slag at 40 wt% was mixed with phenolic resin at 20 wt%, and the remaining 40 wt% consisted of graphite, steel fiber, and alumina. The particle size of palm slag was -600 µm. The brake pad manufacturing method involved varying compaction pressures of 10, 20, 40, and 60 tons at a temperature of 150 °C, with a curing time of 5 minutes. The research results indicate that the 40 wt% palm slag filler with a compaction pressure of 60 tons produced a compressive strength of 57 MPa, Rockwell E hardness of 60 HRE, density of 2.02 g/cm³, volume wear of 0.89 x 10-3 cm³, and wear rate of approximately 0.89 x 10-12 m³/m. The study concludes that palm slag possesses mechanical characteristics that can be utilized as an alternative filler material for brake pad composites.

Further research was conducted by (Ruzaidi-Gazali, et al., 2013) [13] in Table 3, to compare the mechanical properties and observe the filler morphology characteristics of Palm Slag (40 wt%), Calcium Carbonate ($CaCO_3$) (40 wt%), and dolomite (40 wt%) for brake pad composites. The composition of the other components in the brake pad composite materials is as follows: phenolic resin (20 wt%), graphite (10 wt%), steel fiber (20 wt%), and alumina (10 wt%). Brake pad samples were hot-pressed at a pressure of 60 tons, a temperature of 150 °C, and cured for 5 minutes. Palm slag used as a filler material for the brake pad composite had the highest hardness value of 9 Rockwell E and a density of 2.02 g/cm³. The research concluded that fillers from palm slag and calcium carbonate have better wear resistance compared to dolomite fillers (Chand, et al., 2004) [16].

In another study, Khoni, et al. (2018) [17] studied the characterizing of the mechanical properties using fillers from palm slag and tire dust. The ratio of palm slag to tire dust was

Tabel 4: Results of fly ash waste research as composite brake pad filler

Author	**Öztürk & Mutlu (2015) [23]**	**Öztürk & Mutlu (2015) [23]**	**Öztürk & Mutlu (2015) [23]**	**Mohanty & Chugh (2007) [24]**	**Mohanty & Chugh (2007) [24]**	**Mohanty & Chugh (2007) [24]**	**Dadkar, et al. (2009) [22]**
Optimum Formulation (wt%)	Fly Ash (65)	Fly Ash (35), Zinc Borate (30)	Fly Ash (60), Zinc Borate (5)	Fly Ash (60), Phenolic Resin (20)	Fly Ash (55), Phenolic Resin (20)	Fly Ash (60), Phenolic Resin (20)	Fly Ash (80), Phenolic Resin (20)
Ingredients Formulation (wt%)	Phenolic Resin, Lapinus RB 220/Kevlar Pulp, hexa Boron Nitride, Boron Carbide (35)	Phenolic Resin, Lapinus RB 220/Kevlar Pulp, hexa Boron Nitride, Boron Carbide (35)	Phenolic Resin, Lapinus RB 220/Kevlar Pulp, hexa Boron Nitride, Boron Carbide (35)	Glass Fiber (15), Aluminum Fiber (5)	Aramid Pulp (5), Potasium Titanate (10), Graphite (10)	Aramid Pulp (5), Potasium Titanate (5), Graphite (5), Copper Fiber (5)	Aramid Pulp (5),
Manufacturing Process	Hot press 15 Mpa, 150°C, 15 min	Hot press 15 Mpa, 150°C, 15 min	Hot press 15 Mpa, 150°C, 15 min	Hot press 15, Mpa, 180°C, 15 min	Hot press 180°C, 15 min	Hot press 180°C, 15 min	Hot press 15 Mpa,, 155°C, 15 mi,
Post Cured	180°C, 5hours, atmospheric pressure	180°C, 5hours, atmospheric pressure	180°C, 5hours, atmospheric pressure	180°C, 4 hours, atmospheric pressure	180°C, 4 hours, atmospheric pressure	180°C, 4 hours, atmospheric pressure	165°C, 5 hours, atmospheric pressure
Variable Optimum	NA	NA	NA	NA	NA	NA	80/20
Particle Size (µm)	10-30	10-30	10-30	200	200	200	100 mesh
Density (g/cm3)	1.8	1.89	1.79	NA	NA	NA	1.91
Porosity	NA	NA	NA	NA	NA	NA	NA
Wear rate (m^3/m x 10^{-13})	9.8	3	7.3	NA	NA	NA	NA
Wear Volume (cm^3 x 10^{-3})	98	30	70	NA	NA	NA	NA
Coefficient Of Friction (COF) (µ)	0.57	0.47	0.59	0.22	0.25	0.4	0.31
Hardness (Rockwell M)	77	65	86	NA	NA	NA	**115**
% Fade	NA	NA	NA	NA	NA	NA	**30**
% Recovery	NA	NA	NA	NA	NA	NA	**140**
Compressive strength (Mpa)	NA	NA	NA	NA	NA	NA	Na

varied as (0,40), (10,30), (20,20), (30,10), and (40,0) wt%. Additional materials used include phenolic resin (20 wt%), graphite (10 wt%), steel fiber (20 wt%), and alumina (10 wt%). The particle size of the filler particles used was 150 µm, 300 µm, and 600 µm. The research results showed that the palm slag formulation at 40 wt% with a particle size of 600 µm had porosity value of 37.97%, a density value of 2.25, a hardness value of 55 Mpa, compressive strength of 160 Mpa, and a specific wear rate of 8.5 x 10-12 m^3/m. Another formulation using a particle size distribution of 600 µm, with 30% palm slag and 10% tire dust, yielded the best performance, with a density value of 2.22 g/cm^3, a hardness value of 48 Mpa, a compressive strength of 150 Mpa, and the lowest specific wear rate of 3 x 10^{-12} m^3/m.

The study by (Ruzaidi-Gazali,, et al., 2020) [18] combines palm slag and tire dust waste with variations in the weight fractions of palm slag and tire dust, namely (40:0), (30:10), (20:20), (10:30), and (0:40). Other composing materials include polyester 20 wt%, steel fiber 20 wt%, alumina 10 wt%, and graphite 10 wt%. The research results demonstrate that the composition with a weight fraction of 30 wt% palm slag and 10 wt% tire dust has a specific wear rate of 5.7 x 10-13 m^3/m and a volume wear of approximately 0.57 x 10-3 cm^3. The Rockwell E hardness value is 80, with particle size distribution ranging from 600 µm to 1 mm. Furthermore, the study also analyzed the influence of particle size distribution of 150 µm, 300 µm, and 600 µm on the formulation of 30 wt% palm slag and 10 wt% tire dust. The results obtained indicate that particles with a size of 600 µm have the highest hardness level, reaching a value of 87 Rockwell E, and the lowest specific wear rate of 5.2 x 10-13 m^3/m.

2.2 Fly Ash

Fly ash is a byproduct produced from coal-fired power plants, containing fine particles that can cause various serious health issues such as silicosis, lung fibrosis, bronchitis, pneumonitis, irritation to the eyes, skin, nose, throat, and respiratory tract (Basu, et al., 2009) [19], (Kishor, et al., 2009) [20]. Fly ash consists of inorganic materials that have undergone fusion during combustion and particles sized between 0.0740-0.005 mm. The utilization of fly ash as a composite material for brake pads has been widely explored, as shown in Table 4. According to Table 5, most fly ash contains compounds such as SiO_2, Al2O3, $CaSO_4$, and unburned carbon, with fine particles (average particle size of 10-30 µm) generated at high temperatures, above 1000 °C (Acosta, 2009) [21].

Dadkar, et al., (2009) [22] conducted research to characterize and tribologically evaluated the increase in fly ash content in India as a composite filler with the addition of additives such as 5% aramid fiber. The research results indicated 80% fly ash content exhibited the best coefficient of friction performance at 0.23, a density value of 1.91, the highest hardness value of 115, and the lowest fading and recovery values at 30% and 140%, respectively.

Table 5: Composition of fly ash compounds (Dadkar, et al., 2009) [22]

Major oxide composition	(wt.%)
CaO	1
SiO_2	60.12
Al_2O_3	30.16
Fe_2O_3	6.36

Table 6: Composition of fly ash compounds in Turkey (Öztürk & Mutlu, 2015) [23]

Major oxide composition	(wt.%)
CaO	2.65
SiO_2	56.09
Al_2O_3	20.60
Fe_2O_3	11.01
MgO	4.53
NaO	1.6

Table 7: Composition of fly ash compounds (Mohanty & Chugh, 2007) [24]

Major oxide composition	(wt.%)
CaO	20.9
SiO_2	31.3
Al_2O_3	10.6
Fe_2O_3	8. 3
MgO	0.4
NaO	1.6
SO_3	12.8
K_2O	1.1
Na_2O	0.4

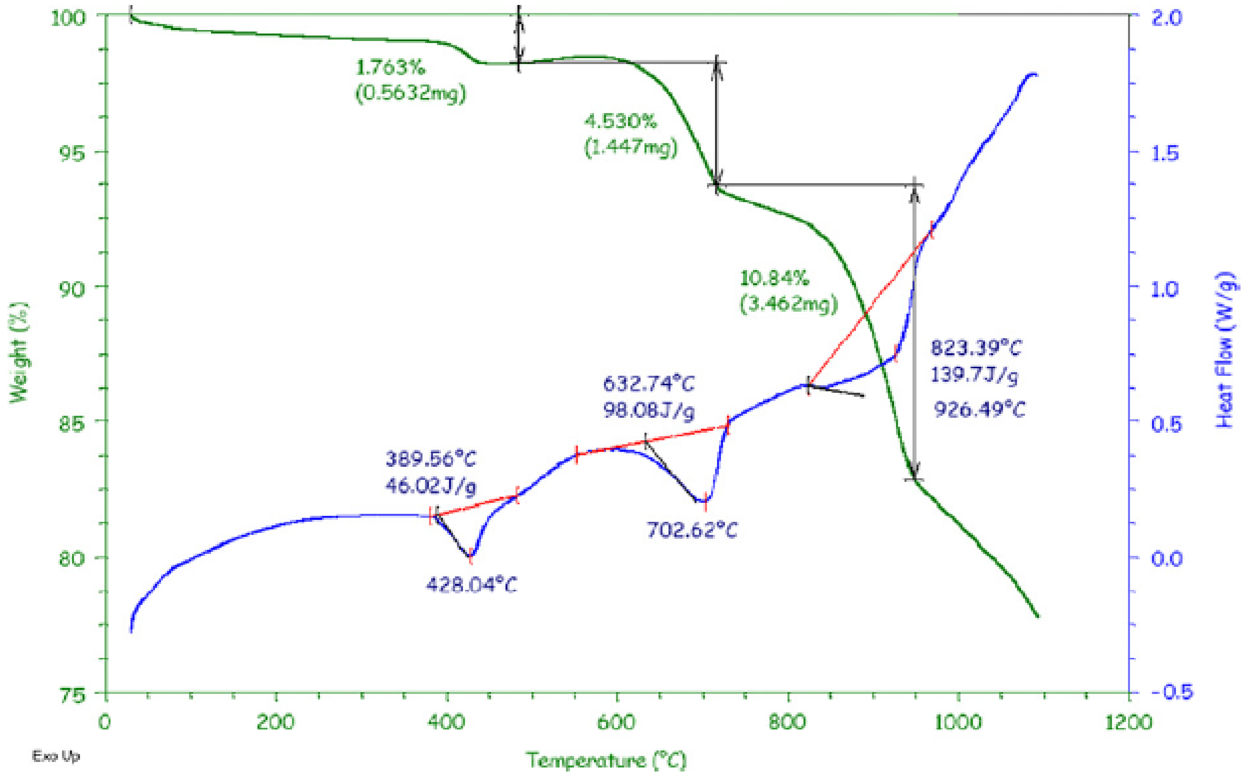

Figure 2. Results of TGA testing on fly ash waste (Mohanty & Chugh, 2007) [24]

Tabel 8: Results of CBPD waste research as composite brake pad filler

Author	**Singh, 2021 [28]**	**Singh, 2021 [28]**	**Singh, 2023 [32]**	**Singh, 2023 [32]**	**Singh, 2023 [32]**
Optimum Formulation (wt%)	CBPD (50)	CBPD (50)	CBPD (30), Barium Sulfate (20), Phenol Formaldehyde (10)	CBPD (50), Phenol Formaldehyde (10)	CKD (70), Phenolic Resin (10)
Ingredients Formulation (wt%)	Phenolic Resin, Fiber, Solid Lubricant (50)	Phenolic Resin, Fiber, Solid Lubricant (50)	Lapinus Fiber (10), Steel Fiber (10), Kevlar (5), Vermiculite (5), Alumina (5), Graphite (5)	Lapinus Fiber (10), Steel Fiber (10), Kevlar (5), Vermiculite (5), Alumina (5), Graphite (5)	Lapinus Fiber (10), Kevlar (5), Graphite (5)
Manufacturing Process	Hot Pressing 15 Mpa, 155^{0}C, 10 Min,	Hot Pressing 15 Mpa, 155^{0}C, 10 Min,	Hot Pressing 100 bar, 155^{0}C, 10 Min	Hot Pressing 100 bar, 155^{0}C, 10 Min	Hot Pressing 15 Mpa, 155^{0}C, 10 Min
Post Cured	160^{0}C, 4 hrs	160^{0}C, 4 hrs	170^{0}C, 4 hrs	170^{0}C, 4 hrs	160^{0}C, 6 hrs
Variable Optimum	Particle Size 600-700	Particle Size 10-25	325 mesh	325 mesh	NA
Particle Size (µm)	600-700	10-25	42	42	NA
Density (g/cm^{3})	Na	NA	NA	NA	2.02
Porosity	7.56	4.48	NA	NA	7.40
Wear rate (m^{3}/m x 10^{-13})	8.2	5.6	Na	Na	NA
Wear Volume (cm^{3} x 10^{-3})	80	55	Na	Na	NA
Coefficient Of Friction (COF) (µ)	0.39	0.36	0.361	0.4	0.243
fade (%)	30	38	20	16	11.53
Recovery (%)	134	117	123.27	114.20	108.3
Hardness (Rockwell R)	96	104	NA	NA	114

Furthermore, (Öztürk & Mutlu, 2015) [23] conducted an analysis of the content of fly ash (FA) in Turkey, as shown in Table 6, by blending zinc borate (ZB) to observe the mechanical and tribology properties of composite brake pad materials. The research results indicated that composite materials containing 0-5% ZB and 65-60% FA exhibited better friction stability and fade resistance compared to materials containing 10-35% ZB and 55-30% FA. The composite filler with 5% ZB and 60% FA showed a maximum coefficient of friction of 0.65. On the other hand, the specific wear rate of the composite decreased with increasing ZB and decreasing FA

Mohanty & Chugh (2007) [24] focused on fly ash waste from a power plant in Illinois to examine chemical composition (Table 7). The results of TGA and DSC testing in Figure 2 showed the fly ash experienced a weight loss of up to 6.3% in the temperature range of 389, 632, and 823°C. Although vehicle brake operations rarely reach temperatures of 800°C, the lost material consists of volatile components that play an insignificant role as composite fillers. The use of fly ash exceeding 50% can increase the friction coefficient to 0.35-0.4 and reduce the wear rate to less than 12%.

2.3 Cement Plant Waste

Cement is a widely used material in the construction industry and is often considered a fundamental foundation in building. However, the cement industry produces a byproduct known as "Cement By-Pass Dust" (CBPD), collected from the bottom of dust filters (Czapik, et al., 2020) [25]. According to (Bai, et al., 2023) [26] millions of tons of CBPD are released into the atmosphere annually, causing significant pollution issues worldwide. The increasing production of CBPD leads to higher disposal costs, making it more attractive to find ways to recover and reuse CBPD (Abdel-Gawwad, et al., 2021) [27].

Table 9: Composition chemical of CPBD (Singh, 2021) [28]

Major oxide composition	(wt.%)
Ca	37.44
Si	5.98
O	51.57
Fe	1.6
Al	2.28
S	1.14

Most CBPD waste is reused in the cement manufacturing process, although a considerable amount is still disposed of, causing serious environmental impacts as reported by (Saleh, et al., 2018) [29]. According to studies by (Singh, et al., 2016) [30] and (Czapik, et al., 2020) [25] CBPD contains significant amounts of silicon dioxide, calcium oxide, aluminum oxide, and other compounds that can be used in the formulation of brake pad composites. Available CBPD waste has low management costs when used as a raw material for composite fillers and provides significant economic benefits and positive environmental impacts. Table 8 presents some research studies that utilize CBPD waste as composite brake pad fillers.

According to (Singh, et al., 2016) [30] materials used in brake pad composite manufacturing are generally grouped into five categories: binders, fillers, fibers, abrasive materials, and lubricants. In a study conducted by (Singh, et al., 2015) [31] was shown that waste from cement processing and phenolic resin had the highest density values and high friction stability, although both exhibited low wear performance.

Research by (Singh, 2021) [28] characterized CBPD and evaluated its mechanical properties as a composite brake pad filler, focusing on tribological characteristics based on particle size distribution, namely 10–25 µm, 88–105 µm, 210–250 µm, 354–400 µm, and 600–700 µm. The main formulation used included 10% phenolic resin, fibers (Kevlar, lapinus, steel; ratio 1:2:2) (wt 25%), graphite (wt 5%), vermiculite (wt 5%), and alumina (wt 5%). Table 9 displays the results of the chemical composition testing of CBPD. The research results indicated that composites with CBPD particle sizes of 600–700 µm had the highest wear rate at 8.2, the highest normal friction coefficient at 0.3, the highest recovery value at 134%, and the lowest fading value at 30%. Meanwhile, CBPD with particle sizes of 10–25 µm had the lowest wear rate at 5.5, the lowest normal friction coefficient at 0.36, the lowest recovery value at 117%, and the highest fading value at 38%.

Recent research conducted by (Singh, 2023) [32] evaluated the use of CBPD from a cement plant in Himachal Pradesh, India, as a filler material for brake pads. The chemical composition testing results of CBPD are presented in Table 10. This research considered the influence of the combination of CBPD and barium sulfate ($BaSO_4$) on the tribological properties of composite brake pads.

The research results showed that a significant increase in CBPD particle concentration resulted in improved performance and friction stability, while fluctuations, wear rates, and disc temperature increases were lower. The composite formulation with 30% CBPD and 20% $BaSO_4$ exhibited the highest friction performance at 0.361, optimal friction stability at 0.76, and the lowest friction variability at 0.60. Additionally, the recovery value reached 123.27%. Compared to barium sulfate, the increased weight of CBPD proved to have better friction performance and fading values but lower friction fluctuations and wear. To optimize the brake pad composite performance from CBPD waste, the concentration needs to be adjusted. Higher concentrations of CBPD will be required to increase the hardness of the composite material, although it may lead to increased wear.

Table 10: Composition chemical of cpbd cement plant in himachal pradesh (Singh, 2023) [32]

Major oxide composition	(wt.%)
Ca	40.57
Si	4.74
O	50.62
Fe	2.08
Al	1.15
S	0.85

3.0 DISCUSSION

3.1 Evaluation of Filler Types Influence on Mechanical Characteristics of Brake Pad Composites

Density testing is defined as the ratio of mass to volume. It is necessary to identify the specific gravity of the components of brake pad composite materials formed from the mixture of different materials. Figure 3 presents the results of several studies identifying the influence of composite fillers from waste on density values in brake pad composites.

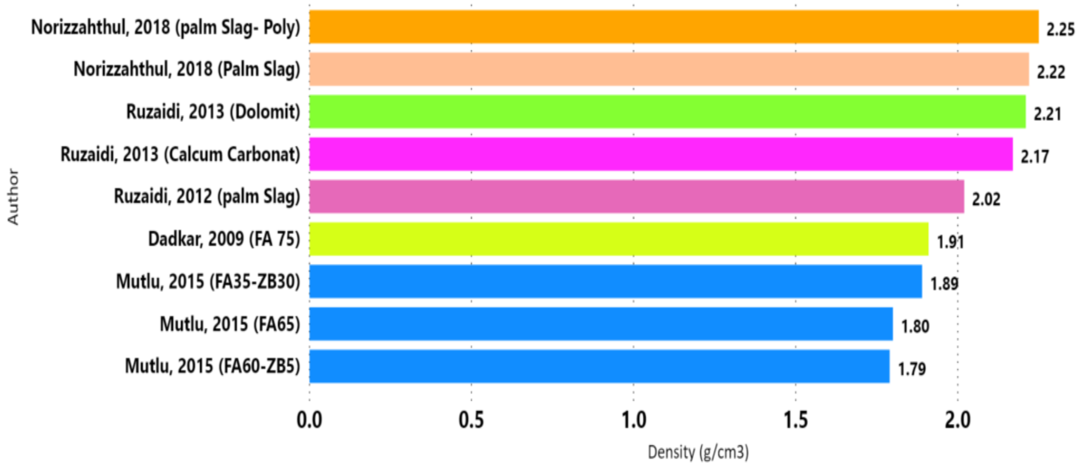

Figure 3: Density values from various studies

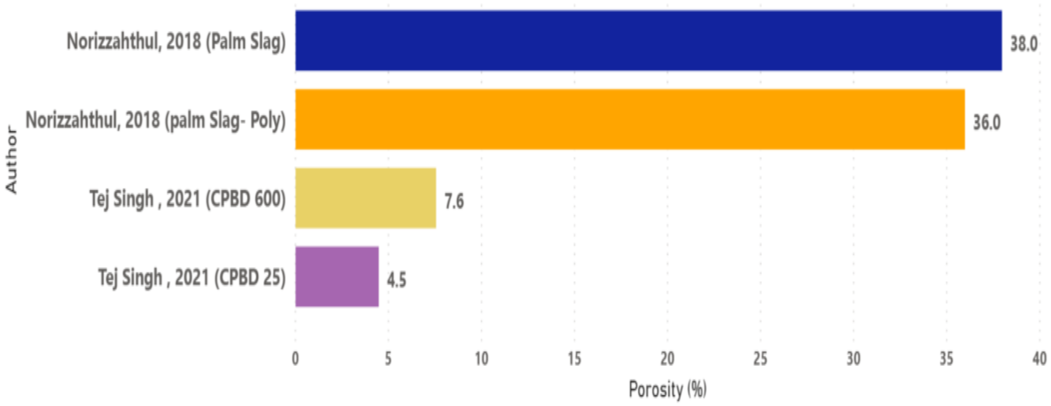

Figure 4: Results of porosity testing for palm slag waste and CBPD

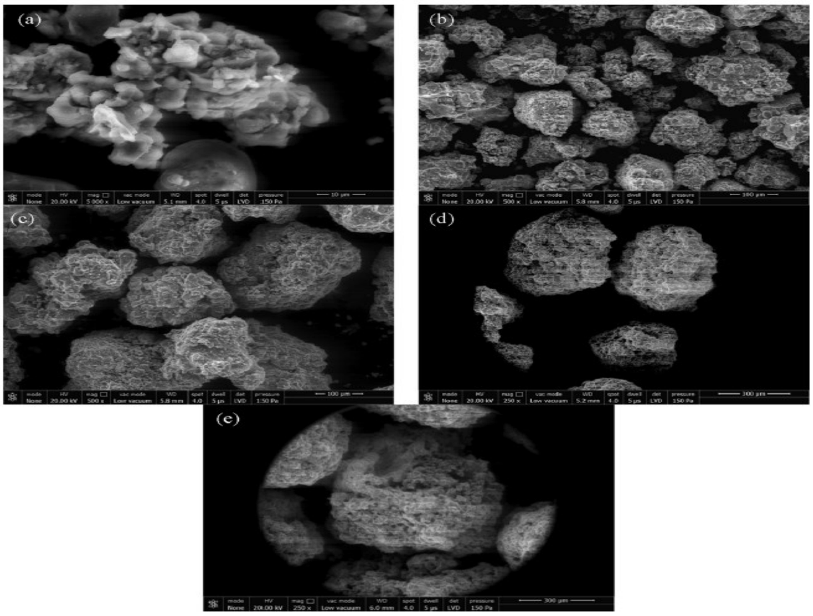

Figure 5: *SEM images* of CBPD *particles*: (a) 10–25 µm, b) 88–105 µm, (c) 210–250 µm, (d) 354–400 µm and (e) 600–700 µm [28]

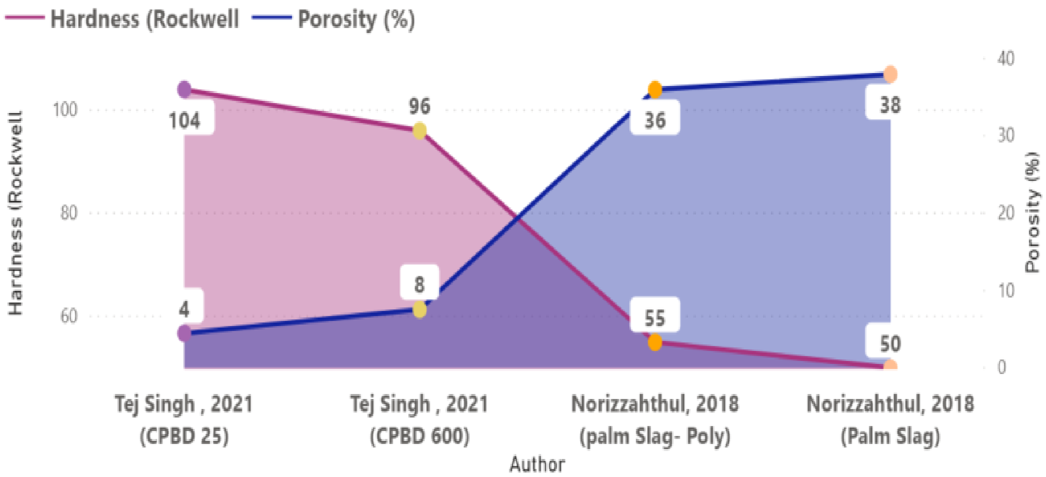

Figure 6: Trends of hardness values in relation to percentage of porosity

The highest density value is 2.25 in the study by (Khoni, et al., 2018) [17], using a composite filler from fly ash waste with a composition of 40% palm slag, particle size 600 µm, green body compaction with a pressure of 30 MPa, and hot pressing at 60 tons at 150°C.

The high and low values of brake pad composite density are influenced, among other factors, by the pressure during the compaction manufacturing process. With increased pressure inside the mold, the density value will increase, and it will inevitably reduce the thickness of the composite material. This has been proven in the study by (Kawabe, et al., 2011) [33], with a mechanical and morphological analysis of the compressive ability of brake pad materials, and in the study by (Guo, et al., 2009) [34], showing that pressure inside the mold significantly affects the density and compressive strength of composite materials.

Figure 4 shows the results of porosity testing for several wastes used as brake pad composite fillers. Porosity is a condition where there is a concentration of high stress that allows crack propagation on the surface or subsurface. High porosity values are caused by a large number of cavities due to low compaction pressure during the manufacturing process, as reported in the study by (Singh, 2021) [28], which observed the morphology of CBPD waste through SEM observations, as presented in Figure 5.

The study by (Kim, et al., 2008) [35], assessed the compaction influence, showing a similar pattern with porosity, where high porosity results in higher compressibility or compaction values. In his research, (Rothon & Hancock, 2003) [36], also observed the compaction effect inside the mold, causing small-sized particles to fill the cavities in the composite structure until most of the cavities were fully occupied. Different particle sizes in the composite brake pad material constituents will push each other in response to high-pressure effects inside the mold. The movement of these particles causes the gaps between particles to become smaller, lowering the height, increasing composite densification, and reducing porosity values, as seen in Figure 6 shows the hardness values increase with decreasing porosity.

3.2 Analysis of the Effect of Filler Size Distribution on the Mechanical Characteristics of the Composite

The waste filler content containing minerals such as SiO_2, CaO, and Fe_2O_3 has the ability to enhance mechanical hardness by forming strong adhesive bonds between particles and the matrix. The hardness properties of composite materials are also influenced by density values, so generally, composites with higher density will exhibit higher hardness values, as observed in the study conducted by (Manoharan, et al., 2019) [37].

Figure 7 presents the hardness test results for various wastes used as composite brake pad fillers. Studies conducted by (Singh, 2021) [28], (Ruzaidi, et al., 2020) [18] and (Dadkar, et al., 2009) [22] have met the hardness standards of commercially produced asbestos. The highest hardness value was obtained from the combination of 75% fly ash waste with a particle size of 149 µm, using phenolic resin as the binder in the research conducted by (Dadkar, et al., 2009) [22].

The mixing method with compaction of smaller particle materials in the composite matrix results in higher density. This has been studied by (Singh, 2021) [28] where the particle size of the CBPD waste filler below 25 µm has better hardness compared to particles sized 600 µm, as seen in Figure 8. Another study by (Kumar & Bijwe, 2010) [38] indicates that porosity is generated by a large particle size distribution or irregular particle size distribution. Experiments with composite fillers such as Fly Ash-Zinc Borate by (Öztürk, & Mutlu 2015) [23] Palm Slag-Tire Dust by Ruzaidi-Gazali,, et al., 2020) [18], CBPD by (Singh, 2021) [28] and Palm Slag by (Khoni, et al., 2018) [17] in Figure 9 show that these wastes have better wear rates than commercially produced asbestos.

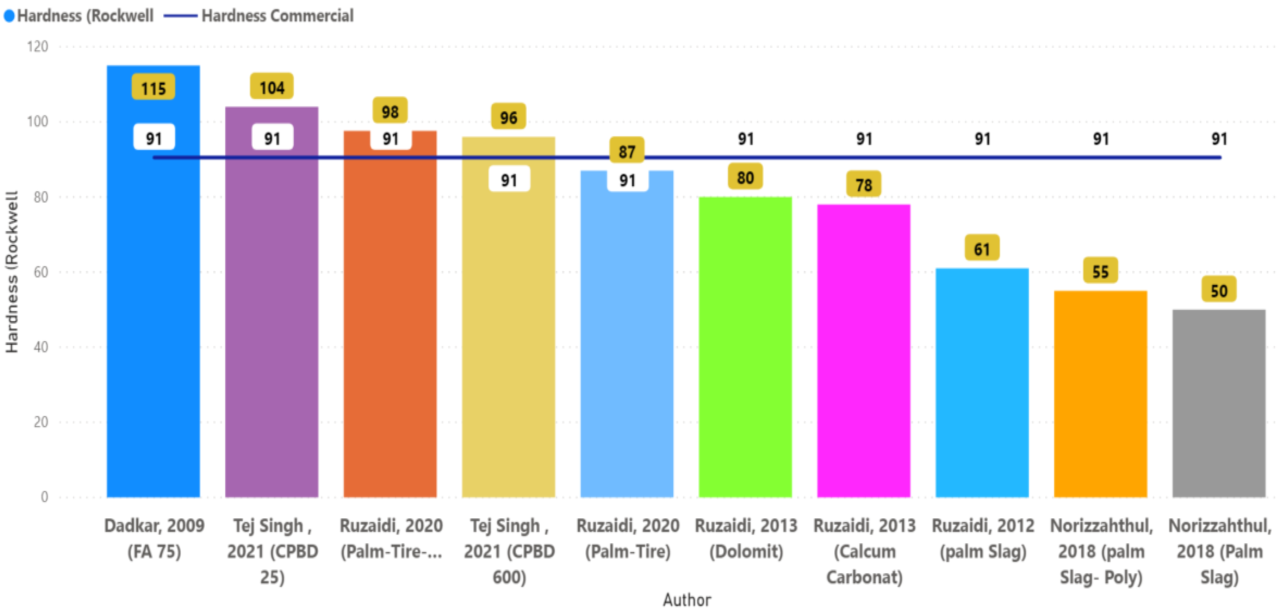

Figure 7: Research on hardness test results

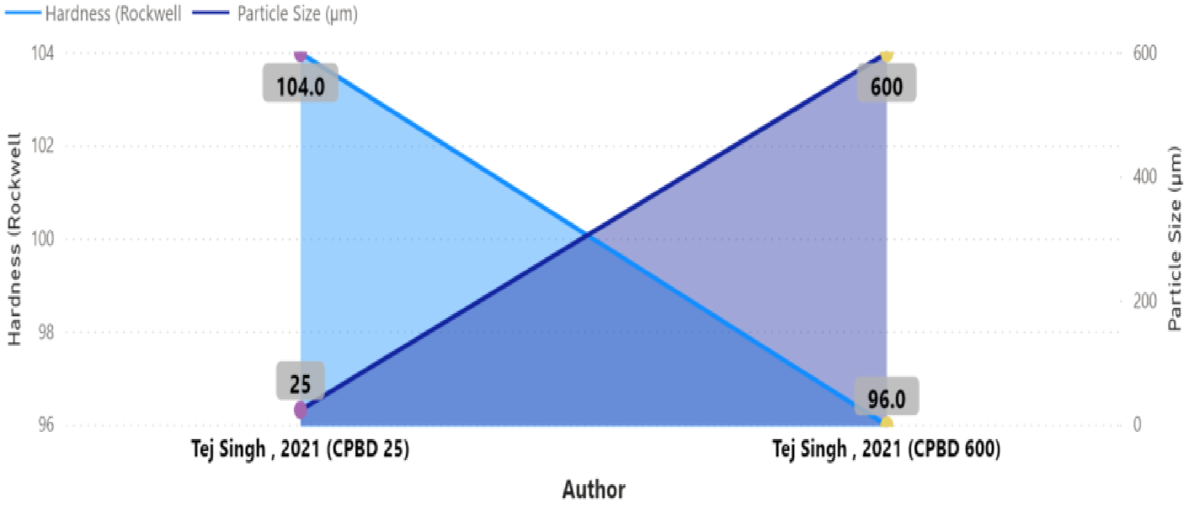

Figure 8: The influence of particle size distribution on the hardness of the composite

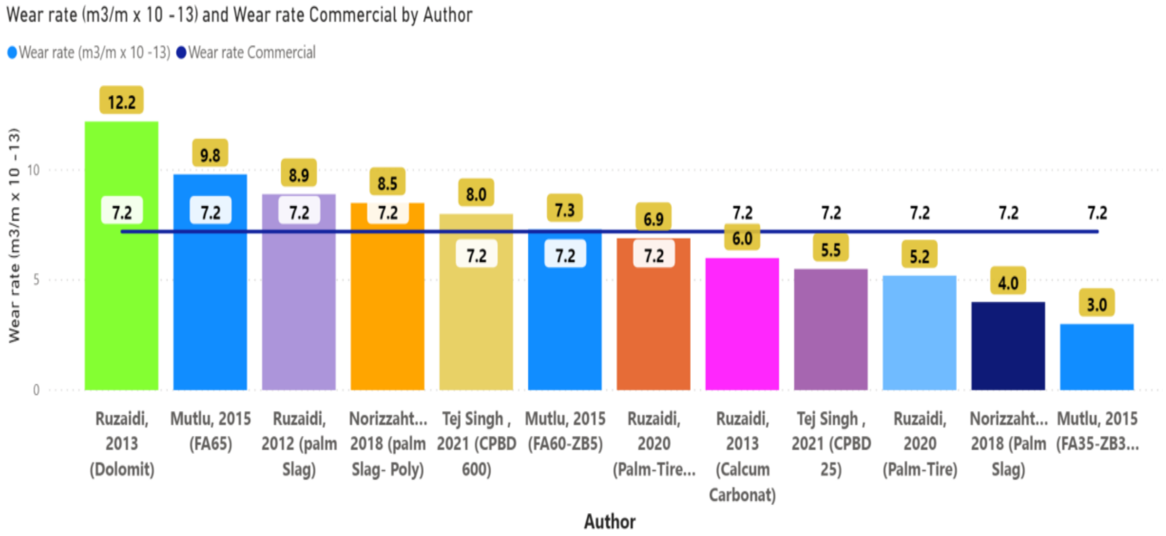

Figure 9: Wear test results from several studies

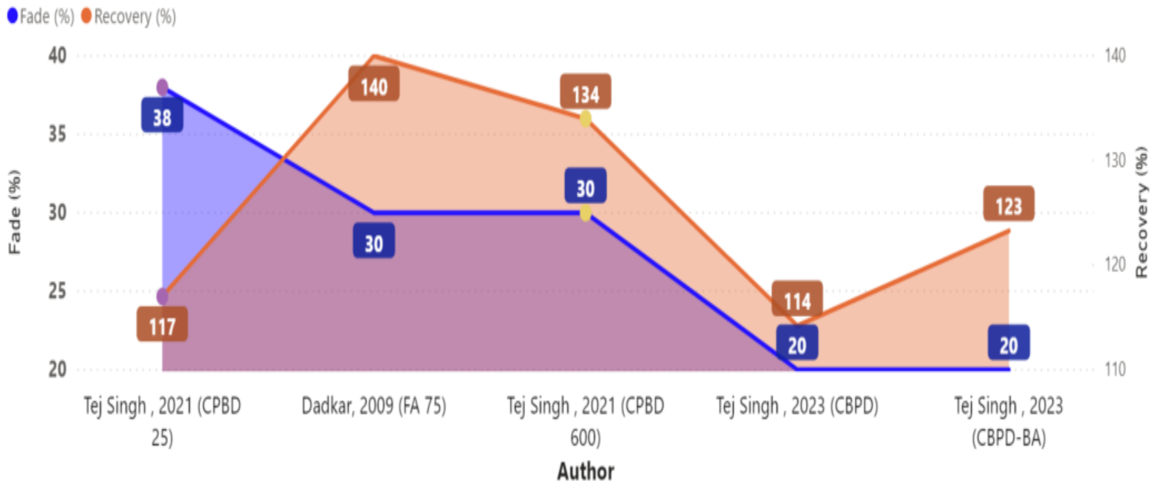

Figure 10: The influence of fading percentage on brake pad recovery percentage

According to (Onyeneke, et al., 2014) [39] a large particle size will reduce the hardness value, but it can also have a positive effect on the mechanical properties of the composite. Larger filler sizes tend to decrease the wear rate of the composite. During the friction of composite particles, there is scratching, compression, and movement on the composite test disc surface to form secondary contact film areas, causing an increase in the actual interaction area. This occurs in the contact areas that increase the amount of resin (reinforcement) distributed on the friction test disc and will dynamically shrink due to the increase in temperature from the shear force, leading to fading in the brake pads. In other words, a decrease in friction causes an increase in temperature (Bijwe, et al., 2006) [40].

According to the research report by (Tiwari, et al., 2014) [41] and (Singh, 2021) [28] smaller particle sizes play a role in three-body abrasion, and the compaction pressure applied serves to protect friction from the secondary contact film layer on the object's surface. Whereas large particle sizes occur due to the formation of two-body and three-body abrasive. Abrasive wear is influenced by the size of the composite filler particles; the larger the particle size, the higher the chance of reducing friction through two-body abrasion. This is supported by the study (Sun, et al., 2018) [42] that particle size plays a crucial role in determining mechanical properties and tribological characteristics. They state that the particle size determines the friction change mechanism at the friction interface. According to them, SiO_2-based ceramic particles that are too large cause excellent wear resistance and fading.

Fading is the decrease in friction performance at high temperatures, and recovery is the improvement in the performance of composite materials during cooling. Good friction power ability in brake pads is determined by the low percentage of fading and the high percentage of recovery, as seen in Figure 10. This is supported by the research by (Singh, 2021) [28] that an increase in the amount of fly ash will reduce fading friction and increase the recovery value.

4.0 CONCLUSION

The utilization of Fly Ash, Palm Slag, and CBPD waste as alternative materials is a sustainable solution that can be utilized in the development of brake pad technology. Wastes containing metal and non-metal compounds such as SiO_2, CaO, Fe_2O_3, Al_2O_3 generally exhibit similarities to Asbestos, which was formerly used as a composite material in brake pads. This similarity creates the potential to use these wastes as alternative materials in the development of composite materials for brake pads, providing a more sustainable and environmentally friendly solution. The use of industrial waste in the production of composite brake pads has proven to offer significant advantages from various perspectives. From an environmental standpoint, this approach has a positive impact by repurposing industrial waste that was previously considered an environmental issue. Technologically, the integration of industrial waste into composite brake pads shows progress in material development and engineering, opening the door for further innovation. Commercially, the utilization of industrial waste can reduce production costs and enhance sustainability, creating more profitable business opportunities.

Compaction value and particle size distribution have a significant impact on the mechanical properties of brake pads, including porosity, density, and hardness. The compaction process plays a crucial role in determining the level of density and porosity in composite materials. The appropriate particle size distribution can also affect the homogeneity of the mixture, influencing the hardness and strength characteristics of the material. Therefore, adjusting the compaction value and particle size distribution is a crucial factor in the development of composite brake pads to ensure that their mechanical properties meet desired requirements. Large particle size distribution plays a crucial role in increasing the density of the material and contributes to the improvement of composite material hardness. Smaller particle size distribution tends to fill the gaps between particles, enhancing material density. Additionally, a smaller particle size distribution significantly contributes to material hardness, as a broad particle size distribution can create a stronger and more homogeneous structure within the composite matrix.

Materials with high hardness levels exhibit low wear rates. Moreover, high hardness values can provide resistance to compressive strength in composites. Large particle distribution may decrease the performance of composite brake pad materials when subjected to an increase in temperature, despite having good recovery values. Larger particles can act as less efficient heat conductors, causing localized temperature increases that can affect the mechanical and thermal properties of the composite material. While having good recovery values, the challenge in designing composite materials with optimal particle distribution is to maintain performance stability at high temperatures by leveraging the recovery advantages of brake pads.

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