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Formulation of brake pad friction composite materials based on low cost natural and industrial eco-friendly local raw materials

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KEYWORDS

Friction
Composite materials
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ABSTRACT

In the framework of this research, experimental study has been realized in order to formulate friction composite materials from local natural and industrial raw materials, such as basalt and volcanic tuff rocks as abrasive materials, and recycled machining waste of brass and rubber particles, for automotive brake pads applications. The prepared friction composite materials were tested to determine their mechanical properties and compare them with commercial equivalent materials used for automotive brake pad applications. On the other hand, the correlation between the mechanical properties and the physical properties of the prepared friction composite materials were studied. Some of the prepared friction composite materials showed a porosity of 0.73%, a flexural strength of 53 (MPa), a Brinell hardness of 55 (HB). These properties can be adjusted by making slight changes of the raw materials proportions in the friction composite materials. The prepared friction composite materials were superior in all of their properties to one commercial friction composite materials available in the local market and used in automotive brake pads applications.

1.0 INTRODUCTION

Friction composite materials are designed to generate friction with predictable average technical life under specific wet or dry operating conditions (Sundarkrishnaa, 2015; Cox, 2012). They are multicomponent materials whose performance is strongly influenced by the choice of their constituents, which are mainly classified into five basic categories, binder material, reinforcing materials, abrasives, lubricants, and friction modifiers (Sundarkrishnaa, 2015, Cox, 2012; Öztürk et al., 2011). Currently, around one billion vehicles of different weight

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range are running on roads. This fleet requires huge quantity of friction composite materials in order to ensure safe and secure braking system meeting the recent governmental regulations concerning environmental issues related to particulate matter emissions from brake pads. On the other hand, the selection of friction composite materials ingredients takes into consideration the economic aspects related to their cost and the increasing utilization of local natural raw materials and industrial wastes. The emerging ecological trend in friction composite materials seeks to minimize their environmental impacts by reducing their emissions of fine particles of 10-micron (PM10) and 2,5-micron (PM2.5) diameters and by benefiting from disposable industrial wastes.

When formulating a friction composite material to withstand the severity of working conditions of brake pads applications, several requirements should be achieved, such as, stability of the friction coefficient, adequate wear rate over the entire operating temperature range, minimal emission of brake dust, low noise and high mechanical properties such as flexural strength, tensile strength, compression strength and hardness (Sundarkrishnaa, 2015). Mechanical properties are considered the most important factors that help to achieve high performance, reliability and safety of braking system.

According to recent regulations in Europe and the United States of America, many of the raw materials commonly used in commercial friction composite materials can have potential negative environmental impact (Yun et al., 2010). In this research, engineered tribological composite materials will be developed for automotive brake pad applications, based on natural low-cost inorganic powders from basalt rocks and volcanic tuff with large deposits in the south of Syria as abrasive materials, and local recycled machining particulate wastes of brass and rubber.

Surojo et al., (2022) studied the effect of rock wool and glass fibers on the flexural strength of friction composite material. The results showed that rock wool had a higher effect on increasing the flexural strength of friction composite materials compared to glass fiber. Priambada et al., (2022) synthesized friction composite materials using cantala fibers at different volume ratios of 0%, 4%, 8% and 12% with and without alkaline treatment. The results showed that alkaline treatment on cantala fibers improved the flexural strength and young's modulus of friction composite materials, especially at volume ratios of 4% and 8% of these fibers. Solomon et al., (2018) developed and evaluated brake pads using groundnut shell (GS) particles as an alternative material to asbestos. Two groups of friction composite materials were developed using different GS particles sizes as a filler. The results obtained indicated that the compression strength and density increased with a decrease in (GS) particles size. Maulana et al., (2018) studied the effect of cantala fibers on the brake pads composite materials. These fibers were used in different volume ratios of 0%, 4%, 8% and 12%. The results showed an increase in flexural strength with an increase in the volume ratio of cantala fibers. Ahmadijokani et al., (2019) prepared friction materials based on phenolic resins with (0-4) % volume ratios of carbon fiber, and studied its impact on the mechanical properties of friction brake pads. Hardness, flexural strength improved, and density decreased with the addition of carbon fiber to the brake pads. Cai et al., (2015) studied the effect of aramid fibers on the mechanical behavior of friction composite materials. The results showed a decrease in porosity and compressive strength and an increase of flexural strength of composite materials with the increase of the fibers volume ratio. Singh et al., (2015) prepared hybrid phenolic friction composite materials to be used in brake pads based on lapinus fibers (rock wool) and aramid fibers. Physical properties such as water absorption, compressibility, and porosity improved with the increase in lapinus fibers, while mechanical properties such as hardness, tensile strength, flexural strength improved with the increase in aramid fibers. (Öztürk et al., 2013) studied the effect of rock wool fibers, ceramic fibers, E glass fibers, and steel fibers on mechanical properties of friction composite materials. Ceramic fiber reinforced composite materials were distinguished by the highest hardness and shear strength. The flexural strength, shear strength and compression strength in steel fiber reinforced composites were lower than their counterparts in other composites. The glass fiber reinforced composite material was distinguished by the highest flexural strength, and low shear resistance.

The development of friction composite materials lends special interest towards developing new eco-friendly and low-cost friction materials (Felipe Ferreira Bindaa et al., 2020; Banu SUGÖZÜ et al., 2021; Vishal Mahale et al., 2019). Non-asbestos organic (NAO) brake friction composites comply with environmental and economic requirements and are, consequently, the most widely developed and used in brake pad (Naveen Kumar et al., 2021). In this context, the present research aims at conducting experimental study in order to formulate friction composite materials for automotive brake pad applications from local natural and industrial raw materials, such as basalt and volcanic tuff rocks as abrasive materials, and recycled machining waste of brass and rubber particles, as additives. To the best of the authors knowledge, few reports have so far considered using basalt, volcanic tuff rocks, waste of brass and rubber particles in brake pad friction composite materials.

2.0 EXPERIMENTAL PROCEDURE

2.1 Materials Selection

Table 1 presents the raw materials powders used in this study with their specific weight, grain size, length (L) and the diameter (R) of the used fibers.

Table 1: Dimensions, form, and specific weight of the materials used.

Function	Material	Specific weight (N/m^3)	Materials form	Dimensions
Binder	Bakelite	1.45	Powder	(80-30) µm
Abrasives	Basalt	2.90	Powder	
	Volcanic tuff	2.62	Powder	
Fillers	Barite	4.48	Powder	
	Rubber	1.10	Crumb	(0.25-0.50) mm
	Brass	8.50	Chips	$\leq$ 250 µm
Reinforcing materials	Basalt fibers	2.80	Short fibers $L = (2 - 6)$ mm	$R = (15 - 18)$ µm
	Steel fibers	7.90		$R = (25 - 75)$ µm
Lubricant	Carbon black HAF N330	1.95	Nanometer powder of (26- 32) nm	

2.2 Experimental Methods

At first, an electric blender grinder DSP model KA3025 was used at a speed of 25000 (rpm) in order to cut the basalt fibers to suitable short fiber lengths according to Table 1, and to disperse them to facilitate their subsequent handling in mixing operations. The materials that are in the form of powders are first mixed to achieve the greatest possible homogeneity. They are then mixed with the fibers to achieve a complete mixture ready for molding operations. The previous mixing operations were carried out using the same electric blender type of (DSP) model (KA3025). Table (2) shows the time of each stage of preparation.

Table 2: The mixing time for each stage of preparation.

Stage	Time (min)
Basalt fiber cutting and dispersing	0.25-0.5
powder mixing	2
Complete mixing of the friction material composition	1

A hydraulic press (CEAST-6707) is used to mold the friction composite material samples. The press ensures the possibility of raising the temperature within the metallic mold during pressing using two heating coils located in the two press platens. The mold is filled with the friction composite material mixture, placed between the press platens, and heated to 160 (°C) (Molding temperature), which is the melting temperature of bakelite. During the molding process, pressure was released three times to allow evaporating gases to escape. The molding cycle (Curing time) is estimated to (12) minutes. After taking the samples out of the mold and cooling them, they are placed in a heat curing oven, within a specific heat program, in order to ensure that the bakelite polymerization process is completed (Postcuring). Figure (1) illustrates the steps of friction composite materials preparation.

The finishing operations were carried out using sandpaper of different grades. The dimensions of the prepared samples were (60 x 8 x 6) mm^3.

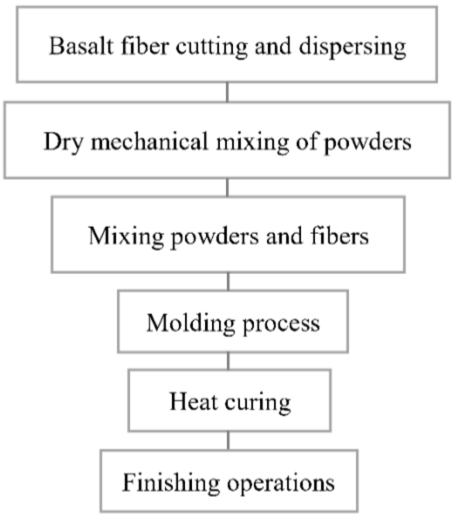

Figure 1: Stages of friction composite materials preparation.

Table (3) shows the experimental conditions for the preparation of bakelite polymer and friction composite materials samples, and their composition.

Table (3): Details of preparation conditions and compositions of sample groups.

	Friction composite materials						
	BAK	F20BS	F20B15S	F20BS20	F20BSC10	F20BSC5	F17BS
Bakelite polymer	100%	20 %	20 %	20 %	20 %	20 %	17 %
Basalt fibers		15%	10%	10%	10%	10%	10%
Steel fibers	-	15%	15%	20%	20%	20%	20%
Basalt		10%	10%	10%	7.5%	10%	9%
Volcanic tuff		10%	10%	10%	7.5%	10%	9%

Carbon black		10%	10%	10%	10%	5%	5%
Rubber		2%	2%	2%	2%	2%	2%
Barite		10%	15%	10%	15%	15%	20%
Brass		8%	8%	8%	8%	8%	8%
Experimental conditions for the preparation of bakelite polymer and friction composite materials samples.							
Molding temperature (°C)	160.00	160.00					
Molding compression (MPa)	18.53	92.67					
Post-curing (°C; hour)	160; 3	160, 3					

2.3 Test Methods

2.3.1 Specific Weight and Porosity Tests

2.3.1.1 Experimental Specific Weight Measurement (ρ_{ex})

Specific weight tests were carried out on bakelite and each friction composite material according to the Archimedes principle, by weighing the sample in air and in distilled water at room temperature and applying the equation (1) (Solomon et al., 2018).

$$\rho_{ex} = \frac{m_1 \cdot \rho_{H_2O}}{m_1 - m_2} \qquad (1)$$

Where ρ_{ex}, the experimental specific weight of the sample(g/cm^3), m_1, sample weight in air (g), m_2, sample weight in distilled water (g), ρ_{H_2O}, specific weight of distilled water at room temperature (g/cm^3).

The specific weight was tested on five samples in each group, and the average value and standard deviation were calculated.

2.3.1.2 Calculation of the Theoretical Specific weight (ρ_{th})

Knowing the specific weight (ρ_i) according to Table (1), and the weight ratio (W_{t_i}) of each constituent in the composition of friction composite materials, the theoretical specific weight was calculated for each friction composite material according to equation (2) (Kar, 2016; Munde et al., 2023).

$$\rho_{th} = \frac{1}{\frac{W_{t_1}}{\rho_1} + \frac{W_{t_2}}{\rho_2} + \cdots + \frac{W_{t_i}}{\rho_i}} \qquad (2)$$

Where ρ_{th}, the theoretical specific weight of the friction composite material sample.

2.3.1.3 Calculation of the Friction Composite Material Porosity (V_p%)

By calculating the theoretical specific weight and measuring the experimental specific weight of samples after heat curing, the porosity of each friction composite materials is calculated according to the equation (3) (Naveen Kumar et al., 2021; Kar, 2016).

$$V_p\% = \frac{\rho_{th} - \rho_{ex}}{\rho_{th}} \times 100 \qquad (3)$$

Where V_p, The volume ratio of pores (porosity) in the prepared friction composite materials. Porosity was determined on five samples in each group, and the average value and standard deviation were calculated.

2.3.2 Mechanical Tests

2.3.2.1 Three-Point Flexural test

The flexural test was performed using the general mechanical testing machine using samples of (60 x 8 x 6) mm^3 dimensions according to (ASTM D790) Standard at a speed of 5 (mm/min). At the end of the test, the (load – deflection) curve is drawn, and flexural parameters are determined on five samples in each group, with the average value and standard deviation.

Flexural Strength (σ_{fs})

It is the strength at which the sample fails, it is calculated according to equation (4) (Callister, 2018; Amit, 2023).

$$\sigma_{fs} = \frac{3.F_{max}.L}{2.b.d^2} \qquad (4)$$

Where σ_{fs}, Flexural strength (MPa), F_{max} maximum load (N), L sample length (mm), d sample thickness (mm), b sample width (mm).

Young's Modulus (E)

The young's modulus was calculated from the equation (5) (Zweben et al., 1979).

$$E = \left[\frac{F_2 - F_1}{\Delta_2 - \Delta_1}\right].\frac{L^3}{4.b.d^3} \qquad (5)$$

Where E, Young's modulus of elasticity (GPa), Δ_1 (mm) sample deflection corresponding to load F_1 (N), Δ_2 (mm) sample deflection corresponding to load F_2 (N), both within the linear part of the (load – deflection) curve.

2.3.2.2 Hardness Testing

Brinell hardness (Brinell HB) was tested using the durometer hardness tester on five samples of each friction composite material by applying a load of 62.5 (kg) on a steel ball with a diameter of 2.5 (mm). The indentation diameter was measured to calculate the Brinell hardness number of each sample from the equation (6) (Callister, 2018), the average value and the standard deviation were calculated for each group.

$$HB = \frac{2P}{\pi D(D - (D^2 - d^2)^{0.5})} \qquad (6)$$

Where P, the applied load (kg), D ball diameter (mm), d indentation diameter (mm).

All the results of the previous tests were compared with their counterpart results for one commercial friction composite materials used in automotive brake pads applications, and will be referred to by the symbol (COM).

3.0 RESULTS AND DISCUSSION

3.1 Specific Weight and Porosity Properties

Figure 2 shows the experimental specific weight of the prepared friction composite materials, their porosity after heat curing, and the experimental specific weight of the commercial friction composite material (COM).

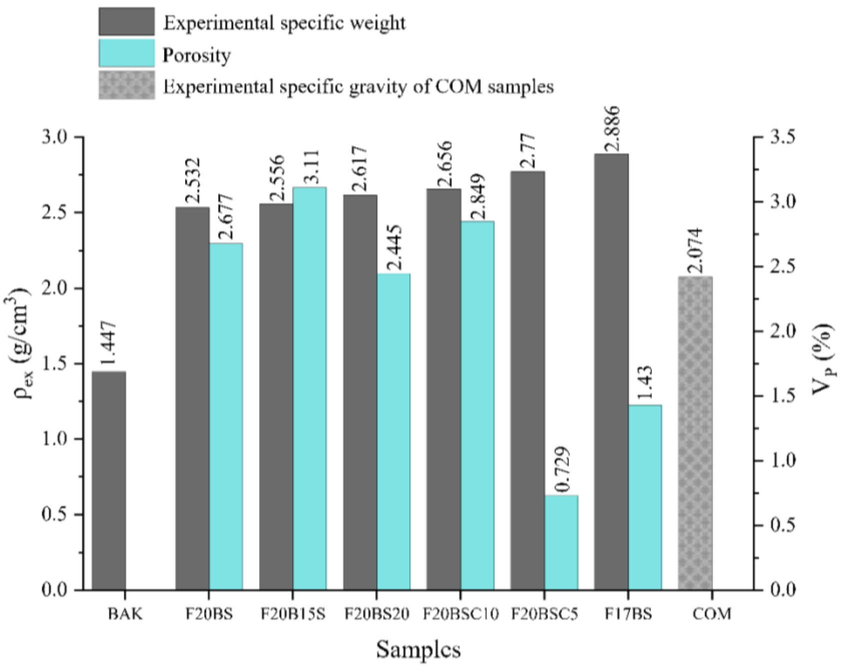

Figure 2: Experimental specific weight and porosity of friction composite materials groups.

Density of the prepared friction composite material varies in the range of 2.5 and 2.9 g.cm^{-3}. These densities are relatively high due to the contribution of the high densities of steel fibers, basalt powder and barite components in the prepared composites. However, density values are within the range of densities of composite brake pad materials and are consistent with other brake friction composite materials (Öztürk et al., 2011; Ahmadijokani et al., 2019; Cai et al., 2015; Singh et al., 2015; Öztürk et al., 2013; Crăciun et al., 2017; Gai et al., 2022; Aitana Tamayo et al. 2021; Pradnya Eknath Kosbe et al., 2019). On the other hand, porosity values of the prepared friction composite material are rather small and vary between 0.729% and 3.110%. The literature indicates porosity values for friction composite materials for brake applications that fall within the range of 5- 25% (Gai et al., 2022).

The friction composite material (F20BSC5) achieved the lowest porosity of 0.729%. This is related to its lowest ratio of carbon black (5%) exhibiting the lowest specific weight compared to the other constituents. Therefore, decreasing carbon black ratio in this composite friction material allows bakelite to better coat its other constituents. This is confirmed by the high porosity of the friction composite material (F20BSC10) due to its high carbon black ratio. Worth to notice that the prepared friction composite materials showed a very good porosity of less than (5%). This could be related to the good fluidity of the bakelite polymer during the molding process which favors its ability to coat the ingredients of the friction composite materials. Second, the use of barite as filler, steel fibers and basalt fibers as reinforcements, and their high densities contributed to decrease their volume ratio in the prepared friction composite materials, allowed better coating the other ingredients by the bakelite melt before its polymerization and crosslinking, and, consequently, decreased the porosity. All that will later reflect good mechanical properties.

3.2 Mechanical Properties

3.2.1 Flexural Strength

Figure 3 shows both flexural strength and Young's modulus of the prepared friction composite materials, and the commercial friction composite material (COM).

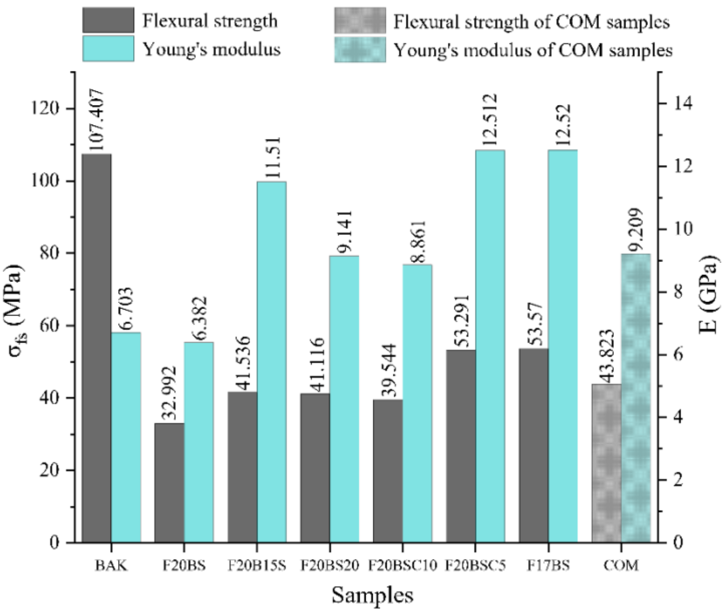

Figure 3: The flexural strength and Young's modulus of the friction composite material groups.

Flexural strength of the prepared friction composite materials varies in the range of 33 to 53 MPa. Flexural strength results are slightly higher than that of the commercial friction composite material (COM) and are consistent with literature (Öztürk et al., 2011; Surojo et al., 2022; Priambada et al., 2022; Solomon et al., 2018; Ahmadijokani et al., 2019; Cai et al., 2015; Singh et al., 2015; Öztürk et al., 2013; Jamasri et al., 2014; Arsada et al., 2018).

The friction composite material (F20BS) achieved the lowest flexural strength of 32.992 (MPa). Consequently, several attempts were made to improve flexural strength by changing the weight ratio of some components in the (F20BS) friction material, in particular, the weight ratio of barite and steel fibers as follows:

i) The increase of barite content, and the decrease of basalt fibers content in the friction composite material (F20B15S) improved the flexural strength to 41.536 (MPa),

ii) The increase of steel fibers content, and the decrease of basalt fibers content in the friction composite material (F20BS20) improved the flexural strength to 41.116 (MPa),

iii) The increase of barite and steel fibers contents, and the decrease of basalt and volcanic tuff contents in the friction composite material (F20BSC10), induced a slight decrease in flexural strength to 39.544 (MPa) in comparison with (F20B15S - F20BS20) friction composite materials. This indicates that basalt and volcanic tuff contributed together to improving the flexural strength of the prepared friction composite material,

iv) The increase of barite and steel fibers contents, and the decrease of basalt fibers and carbon black contents in the friction material (F20BSC5), improved the flexural strength up to 53.291(MPa). This could be due to the reduction of the weight ratio of carbon black to 5%, which reduces its volume ratio in the friction composite material, and reduces the large surface of its nanometric particles, allowing the reduction of the needed bakelite to coat them, and improving bakelite coating of other friction composite material ingredients.

v) The increase of barite and steel fibers contents, and the decrease of basalt fibers, carbon black, basalt, and volcanic tuff contents in the friction composite material (F17BS) improved the flexural strength up to 53.570 (MPa). Thus, the friction composite materials (F20BSC5-F17BS) achieved 50% flexural strength of pure bakelite.

These results could be explained as follows:

i) The high flexural strength of the used bakelite polymer favors the improvement of the flexural strength of its friction composite materials,

ii) The good fluidity of the used bakelite polymer favors its ability to coat the ingredients of the prepared friction composite materials,

iii) The use of barite as a filler, and the high elasticity of steel fibers as a reinforcing material improved the flexural strength of friction composite materials, because their high specific weights decrease their volume ratio in these composites, allowing better bakelite coating of other ingredients. The expected good adhesion properties between the bakelite and these ingredients could be an additional factor. These factors helped in attaining low porosity and, consequently, high flexural strength of the prepared friction composite materials,

iv) The increase in the weight ratio of basalt fibers led to a decrease in the flexural strength of friction composite materials. This could be related to basalt fibers poor dispersion, which reduces their reinforcement effect, from one side, and hinders bakelite coating of the other composite ingredients, on the other side.

The increase of the friction composite materials flexural strength was accompanied with an increase of their Young's modulus. This could be related to the contribution of fibers, and that of the abrasive ingredients in improving the deformation resistance of the friction composite materials. The large flexural strength range of the prepared materials, and their reduced porosity range, allow the control of their mechanical properties by slight adjustment of their ingredient proportions.

By studying the flexural strength and porosity properties of the prepared friction composite materials, Figure 4 shows the improvement of their flexural strength with the decrease in their porosity, which conforms with the general trend of correlation between the mechanical properties of materials and their porosity. The flexural strength of the prepared friction composite materials was competitive with or higher than that of the commercial friction composite materials (COM).

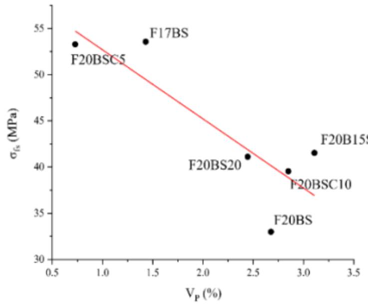

Figure 4: Variation of flexural strength with porosity and composition of the prepared friction composite materials.

3.2.2 Brinell Hardness

Figure 5 shows the Brinell hardness of the studied groups of friction composite materials and its correlation with their flexural strength. Brinell hardness of the studied groups of friction composite materials varies in the range of 36 to 60 HB. These Brinell hardness results exceed that of the commercial friction composite material (COM) and are consistent with literature (Öztürk et al., 2011; Ahmadijokani et al., 2019; Cai et al., 2015; Singh et al., 2015; Öztürk et al., 2013; SUGÖZÜ et al., 2021; Eziwhuo et al., 2024).

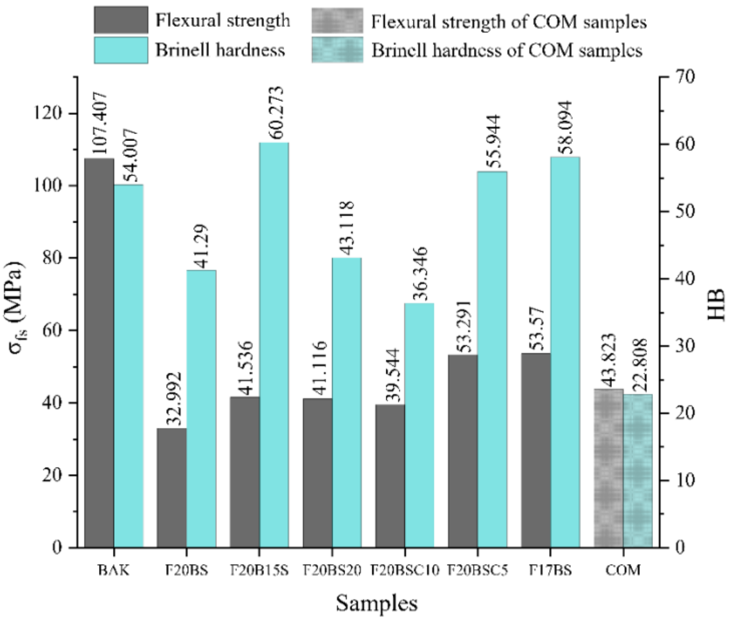

Figure 5: Correlation between Brinell hardness and flexural strength of studied of friction composite materials.

Figure 5 shows a slight decrease in the hardness of the friction composite materials (F20BS) and (F20BSC10) with the increase of their basalt fibers content in comparison with other prepared friction materials. Despite the hardness of basalt fibers, their poor dispersion and aggregation hinder their good coating with bakelite and may lead to easy penetration of their bundles by the hardness indenter. In contrast, steel fibers have improved the hardness by slight increase of their weight ratio, which could be due to the good adhesion between bakelite and steel fibers.

Friction material (F20B15S) achieved the highest hardness of 60.273 (HB) because it contains the highest weight ratio of hard abrasives (basalt and volcanic tuff 20%), the lowest weight ratio of basalt fibers 10%, and the second highest weight ratio of barite 15%. All these contributed to the highest hardness of this material. Friction material (F17BS) achieved a hardness of 58.094 (HB) close to the previous material (F20B15S), because it contains the highest weight ratio of barite (20%).

The Brinell hardness increase with the increase in barite weight ratio could be related to two reasons. First, the ability of the molten bakelite to well coat barite and other friction composite material components. Second, the good adhesion properties between barite and bakelite polymer.

The prepared friction composite materials achieved better hardness than the commercial friction material (COM), due to the use of relatively high hardness basalt and volcanic tuff rocks as abrasives.

The parallel improvement of Brinell hardness and flexural strength was observed in most of the prepared friction composite materials. Friction composite materials (F20B15S-F20BSC5-F17BS) achieved higher hardness than bakelite polymer. Table 4 summarizes the properties of the prepared friction composite materials.

Table (4): Summary of the physical and mechanical properties of the friction composite materials groups.

Friction composite materials	Physical properties		Mechanical properties		
	(ρ_{ex}) Experimental specific weight ($\frac{g}{cm^3}$)	**(V_P%) Porosity**	**(σ_{fs}) Flexural strength (MPa)**	**(E) Young's modulus (GPa)**	**(HB) Brinell hardness**
BAK	1.447 ± 0.01	-	107.407 ± 5.236	6.703 ± 0.079	**54.007 ± 4.717**
F20BS	2.532 ∓ 0.005	2.677 ∓ 0.186	32.992 ∓ 1.516	6.382 ∓ 0.229	**41.290 ± 3.204**
F20B15S	2.556 ∓ 0.006	3.110 ∓ 0.228	41.536 ∓ 2.001	11.510 ∓ 1.168	**60.273 ± 4.130**
F20BS20	2.617 ∓ 0.020	2.445 ∓ 0.742	41.116 ∓ 3.572	9.141 ∓ 0.273	**43.118 ± 1.247**
F20BSC10	2.656 ∓ 0.008	2.849 ∓ 0.292	39.544 ∓ 3.697	8.861 ∓ 0.636	**36.346 ± 2.996**
F20BSC5	2.770 ∓ 0.005	0.729 ∓ 0.168	53.291 ∓ 2.9	12.512 ∓ 0.285	**55.944 ± 3.978**
F17BS	2.886 ∓ 0.011	1.430 ∓ 0.378	53.570 ∓ 7.419	12.520 ∓ 0.729	**58.094 ± 4.516**
COM	2.074 ∓ 0.031	-	43.823 ∓ 6.469	9.209 ∓ 0.988	**22.808 ± 3.272**

Table 4 shows that the properties of the prepared friction composite materials groups compare well with those of developed friction composite materials in recent literature (Naveen Kumar et al., 2021; Zweben et al., 1979; Mithul Naidu et al. 2023; Pradnya Eknath Kosbe et al., 2019; Hamid Ansari Moghadam et al., 2022) and with some commercial counterpart materials (Elakhame et al., 2020).

CONCLUSIONS

In this research, low cost and eco-friendly composite friction materials for brake pads were prepared based on natural inorganic powders from basalt and volcanic tuff rocks with large deposits in the south of Syria as abrasive materials, and recycled machining waste of brass and rubber particles. Specific weight and porosity, flexural strength and hardness of these friction composite materials were studied.

Basalt, volcanic tuff, barite and steel fibers contributed to the improvement of the specific weight, porosity, flexural strength and Brinell hardness of the prepared friction composite materials. In contrast, carbon black and basalt fibers induced decrease of these properties.

The flexural strength and Brinell hardness of the prepared friction composite materials could be controlled by making a slight adjustment in the proportions of their constituents

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