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PAPER

Influence of recycled basalt-aramid fibres integration on the mechanical and thermal properties of brake friction composites

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Abstract

In the brake friction composites (BFCs), fibres take part in significant attention as reinforcement in governing mechanical and thermal-mechanical properties. The current investigation aims to develop hybrid brake friction composites using recycled basalt- aramid fibre integration and to characterise for its mechanical and thermal properties. The experiments related to thermal (heat swell, loss of ignition and thermal conductivity) and mechanical (tensile, compression, flexural and impact) properties were conducted as per industrial standards. From the experimental investigations, it was concluded that fibre inclusion in the BFCs enhanced the mechanical and thermal properties considerably. Further, with the aid of scanning electron microscope (SEM), fracture interfaces of the tested friction composites were analyzed for various characteristics like pullout, void, fibre-matrix bonding etc.

1. Introduction

The friction materials (FMs) before being used in automotive brake vehicles are generally evaluated by its various mechanical and thermal properties in order to quantify its tribological performances [1, 2]. As mechanical properties have been a noteworthy bearing on the composite wear and to support friction. In broad, the performance of FMs is strongly influenced by the selection of reinforcements, i.e., fibres and fillers. It is highly acknowledged in previous studies that predominance of reinforcement fibres have a beneficial influence on its mechanical properties. The mechanical properties of FMs are enhanced ahead of fibre loading as compared to unreinforced one [3]. In polymer tribology, the inclusion of reinforcements is one kind of process to advance the mechanical and tribological properties in order to formulate them further apt under different loading circumstances [4–6]. The reinforcement fibres like natural fibers, fillers, steel fibers, stainless steel fibers, mullite, aramid fibers etc in FM's may perhaps help to get better the strength and thermal stability though the frictional modifiers alter the tribological performances [3–12]. $BaSO_4$ are used as filler while manufacturing the brake pad [13]. It should possess good size, shape and purity for maintaining the performance properties of the developed friction composites. Rather than that many other materials are used in the formulation like granite powder, ulexite, red mud, borax, rice husk etc [14–18]. On occasion, the overall cost of the composite may be reduced by ahead of inclusion of inert filler.

Development of filler and fibre-based BFCs contain superior mechanical properties that have been the essential characteristics of composites in a customized manner. The chance of acquiring unique features, individually or in integration which are not eagerly attained while using one sort of fibre only. For that reason, friction composites developers are studying on the uniting of different category of fibres. Hybrid friction composites are obtained by uniting a two or more, unlike reinforced fibres/fillers within the same matrix. The properties of hybrid composites are superior, and this is not possible in the composites in the case of reinforced composites with a single reinforcement fibre [19, 20]. The assortment of reinforcement is according to their various properties which donates to the whole cost of systems [3]. It is known that around 500 ingredients are available to be used in the brake friction composite. However, the formulations used in current commercial brake friction composites are obtained by a trial and error method.

The hard basalt fibre has been known for its better hardness and mechanical strength and excellent thermal conductivity. The basalt fibre in FMs shows signs of improvement in μ as it hold the tail and a head or shot morphology. The 'shot' being the harder part of the basalt fibre augment stable μ and wear resistance [21]. Öztürk *et al* assessed the effect basalt fibre on mechanical properties of hybrid friction composites and observed that the addition of basalt fibre enhances the mechanical properties of composites significantly [21]. Superior wear resistance, friction stability, excellent filler retention and non abrasiveness to mating surfaces are the key advantages of soft aramid fibre. Aramid fiber has been efficiently engaged in the non-asbestos organic (NAO) composition owing to its superior modulus and strength, and thermal stability, stable and steady μ and synergistic in amalgamation with rock wool in exhibiting low fade behaviours [22]. These fibres make an essential reinforcement in advanced composite and wear part applications such as clutch and brakes. Singh & Patnaik [23] characterised the mechanical properties of aramid-lapinus fibres based friction materials and concluded that mechanical properties of FMs increased with increase in aramid fibre. Mukesh Kumar *et al* [24] assessed the mechanical properties of aramid fibre reinforced hybrid friction composites and provided evidence that addition of aramid fibre reasonably advances strength of the composites. Although friction composites are continuously being developed for a few decades based on virgin fibres, a significant concern takes place towards the performance of FMs. Hence, there is in need of finding innovative reinforcements for FMs manufactures to make an alternative for the current one in order to establish effective braking system. By taking account of previous studies, the recycled fibre combination may be suitable for further improvement of brake friction composites performance.

Eco-friendly recycled fibres are extracted from non-recycled fibres in order to prevent dumping of solid wastes that burdens our landfills and weaken the natural resources of earth. These recycled fibres possess the same chemical and functional properties with a minor difference as well the virgin fibres with cost-effective manner. Accordingly, the present study deals with the development of brake friction composites (BFCs) based on recycled basalt and aramid fibres integration by varying the weight percentage (wt%) that is compensated with barium sulphate ($BaSO_4$) by keeping other parental ingredients as constant. The developed brake friction composites are analyzed for thermal and mechanical properties as per industrial standards.

2. Experimental details

2.1. Materials and methods

In the present study, two different recycled fibres such as basalt and aramid fibre were used as reinforcements. The average length of aramid fibre was 1.25 mm and for basalt fibre was 6 mm. In this study barium sulphate synthetic grade was used which is having mesh size 150 microns. The SEM images of the varying ingredients are given in figures 1(a)–(c). The brake friction composites were fabricated with a size of 200 mm × 200 mm × 6 mm. The fabricated brake friction composites possess thirteen ingredients, such as fibres: recycled basalt and aramid fibres; binders with additives: phenol-formaldehyde resin, crumb rubber, calcium oxide, NBR; functional fillers: cashew friction dust, tin powder, exfoliated vermiculite, kaolin clay; inert filler: synthetic barite ($BaSO_4$); friction modifiers: molykote, graphite and SiC. The formulation with cumulative weight % of each category is shown in table 1.

The developed brake friction composites were designated as RC1, RC2, RC3, RC4 and RC5. Before the fabrication, the ingredients were mixed homogeneously for 20 min. Fibres (recycled basalt and recycled aramid) were mixed for 10 min. Filler particles were added and further mixed for about 6 min. Phenol formaldehyde based binder was added and mixed about another 4 min [25]. First the ingredients were blended in a Lodigee type shear mixer having one shovel rotating at speed of 140 rpm, three chopper rotating at speed of 2800 rpm and 1 kg mix was prepared. Curing was done in compression moulding process in order to toughen the composite as it made from several ingredients. In order to expel the volatiles and gases, five intermediate breathings were given during the curing process of 15 min at a temperature of 150 °C with 10 MPa of pressure. After curing, the composite plate was allowed to post-cure in a hot oven in order to cure the residual resin and to relieve the frozen-in stresses by following step baking process at temperatures of 120 °C 150 °C and 170 °C for 60, 60, 120 min respectively.

2.2. Thermal properties

Three samples were tested from each composites for each test in order to prove the consistency in the results.

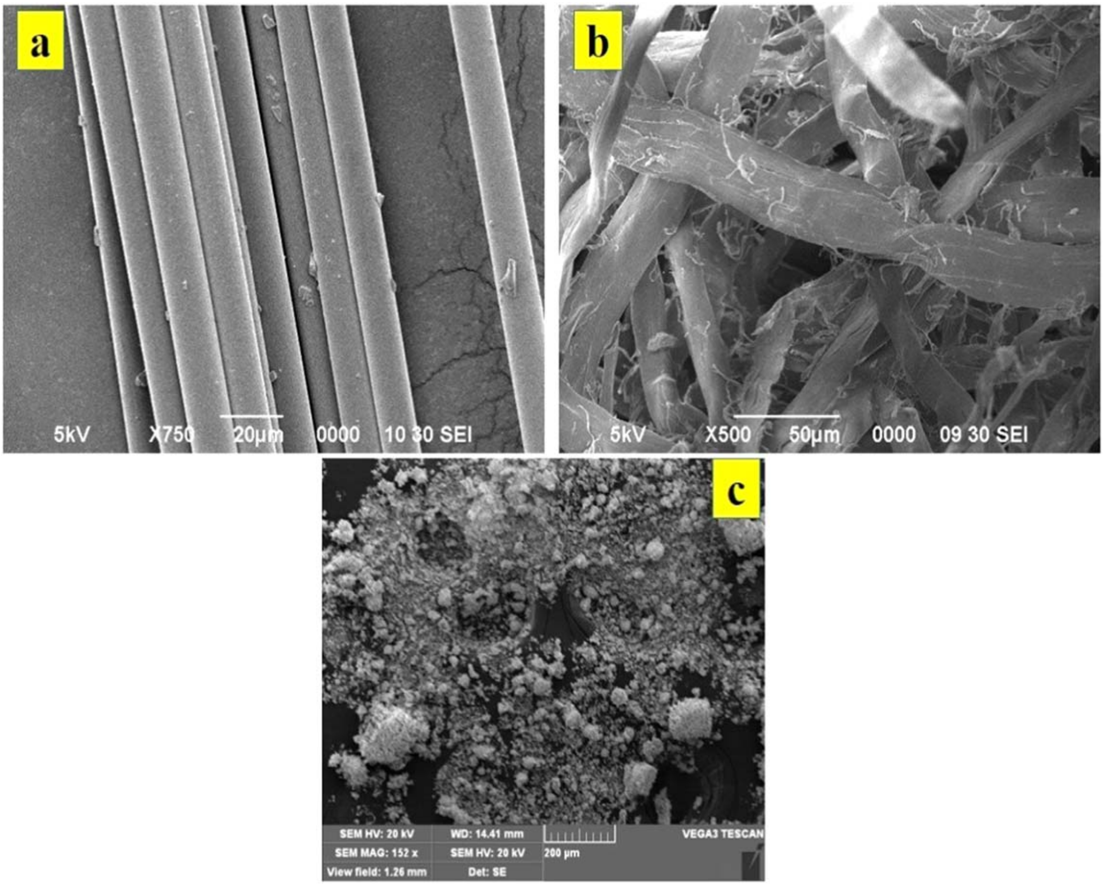

Figure 1. SEM image of (a) Recycled basalt fibre; (b) Recycled aramid fibre; (c) Barium sulphate.

Table 1. Formulation with cumulative weight % of each category for development of brake friction composites.

Composites	RC1 (wt%)	RC2(wt%)	RC3(wt%)	RC4(wt%)	RC5(wt%)
Fibres	25	20	15	10	5
Binders with additives	16	16	16	16	16
Friction Modifiers	18	18	18	18	18
Functional Fillers	41	41	41	41	41
Inert Fillers	0	5	10	15	20

2.2.1. Heat swelling

Initially, the sample thickness was measured to an accuracy of 0.02 mm at ambient temperature at not less than six equally spaced points between 12 to 20 mm from the edge of the brake friction composite samples. The sample was placed in the oven and the temperature was increased to 200 ± 3 °C within a time interval of 30 to 60 min. The sample was then allowed to remain in the same oven for a time period of 30 to 40 min at 200 ± 3 °C. The sample thickness under hot condition was measured at the same point which was initially used at the ambient temperature. The change in the thickness was recorded as the swelling of the composites. A minimum of three samples were tested as per IS 2742 Part 3 of 2014.

2.2.2. Loss of weight on ignition.

A sample of 1 g was weighed accurately in a pre-weighed silica crucible to an accuracy of 3 decimal places. The crucible is then heated in a muffle furnace to a temperature of 800 °C and soaked for a time period of two hours. The crucible is then removed from the furnace and kept in the desiccators and same was weighed again. The calculations are given in equations (1) and (2) for ash content and loss of weight on ignition respectively. The loss of weight on ignition test was carried out as per IS 2742 Part 3 of 2014

$$\text{Ash content}(\%) = (w_3 - w_1/w_2 - w_1) \times 100 \tag{1}$$

$$\text{Loss of weight on ignition}(\%) = 100 - \%\text{ of ash content} \tag{2}$$

w_1- weight of empty crucible
w_2- weight of crucible plus sample before ignition
w_3- weight of crucible and its content after ignition

2.2.3. Acetone extraction

The Soxhlet extractor apparatus was used in the acetone extraction test in order to measure the quantity of uncured resins in friction composites. A fine particle of sample weight required for this test was 2 ± 0.2 g. The accuracy of the sample weight was maintained at 0.001 g and the same was wrapped securely in a filter paper. The wrapped sample was placed in an extraction thimble of 25 mm × 80 mm thick and then transferred to extractor. The process of extraction extended for a period of six hours, until the extractor was almost filled with acetone. The final residue value of acetone was about 15 ml in the flask. The contents in the flask were then transferred to a silica crucible, whose weight was pre-calculated, the same was washed with acetone and the content were again transferred to the same silica crucible. The acetone in the crucible was allowed to evaporate by keeping the same in a water bath and then in the hot air oven for about 10 min at 80 °C. Finally the crucible was weighed in desiccators after cooling as per IS 2742 Part 3 of 2014. The formula used for calculation of acetone extraction is given in equation (3).

$$\text{The \% of acetone extraction} = ((w_3 - w_2)/w_1) \times 100 \tag{3}$$

w_1 = weight of the composite sample (g)
w_2 = weight of empty crucible (g)
w_3 = weight of crucible + extraction (g)

2.2.4. Thermal conductivity

The thermal conductivity of the composites was measured using Laser flash apparatus (Make: NETZSCH; Model, LFA 447 *NanoFlash*™) with a furnace, capable of operation from 25 to 300 °C. The apparatus was equipped with a software-controlled automatic sample changer allowing measurement of up to 4 samples at the same time. The In-Sb detector was used to measure the temperature rise on the back face of the sample. The LFA 447 operates in accordance with ASTM E-1461-13 [26].

2.3. Mechanical properties

Three samples were subjected to test for each set of combination of brake friction composites; consistent test results were reported. The allowable error is 5% as per standard industrial practice. The calibrations of the testing equipment was done as per the national traceability standards by NABL certified laboratories.

2.3.1. Tensile test

For tensile test, Dog bone or dumb-bell shaped sample (size = 165 × 13 × 6 mm^3) was used and a digitalized universal Testing Machine (UTM, Model KIC, Kalpak, S.R No: 121101; test speed = 2 mm min^{-1}, gauge length = 55 mm, load range =10 kN) was used to analyse the tensile properties of the brake friction composites in accordance to ASTM D 638-14.

2.3.2. Compression test

A compressive force is developed in the friction composites when it subjected to an external load. Hence, the composites should possess high compressive strength in order to avoid the failure under the braking load. To recognize on the subject of compressive strength, compressive test samples (sample length: 25 mm, diameter: 12.7 mm) were tested using UTM (speed = 2 mm min^{-1} and load=10 kN) according to ASTM D 695-15.

2.3.3. Flexural test

The Flexural test was carried out on same UTM to quantify the flexural strength of composites using the three-point bending fixture with a crosshead speed of 2 mm min^{-1} according to ASTM D790-10 for a sample of size 130 × 13 × 6 mm^3.

2.3.4. Impact test

The impact test is a notched, single-point impact test which is a direct measure of requirement of kinetic energy to initiate the fracture in the friction composite. The notch (45°) was provided to induce the brittle fracture and to avoid the deformation of the composite under load. This experiment was conducted in accordance with ASTM D256-10 having a sample size of 65 × 13 × 6 mm^3 in Izod impact machine and expressed in terms of Joules.

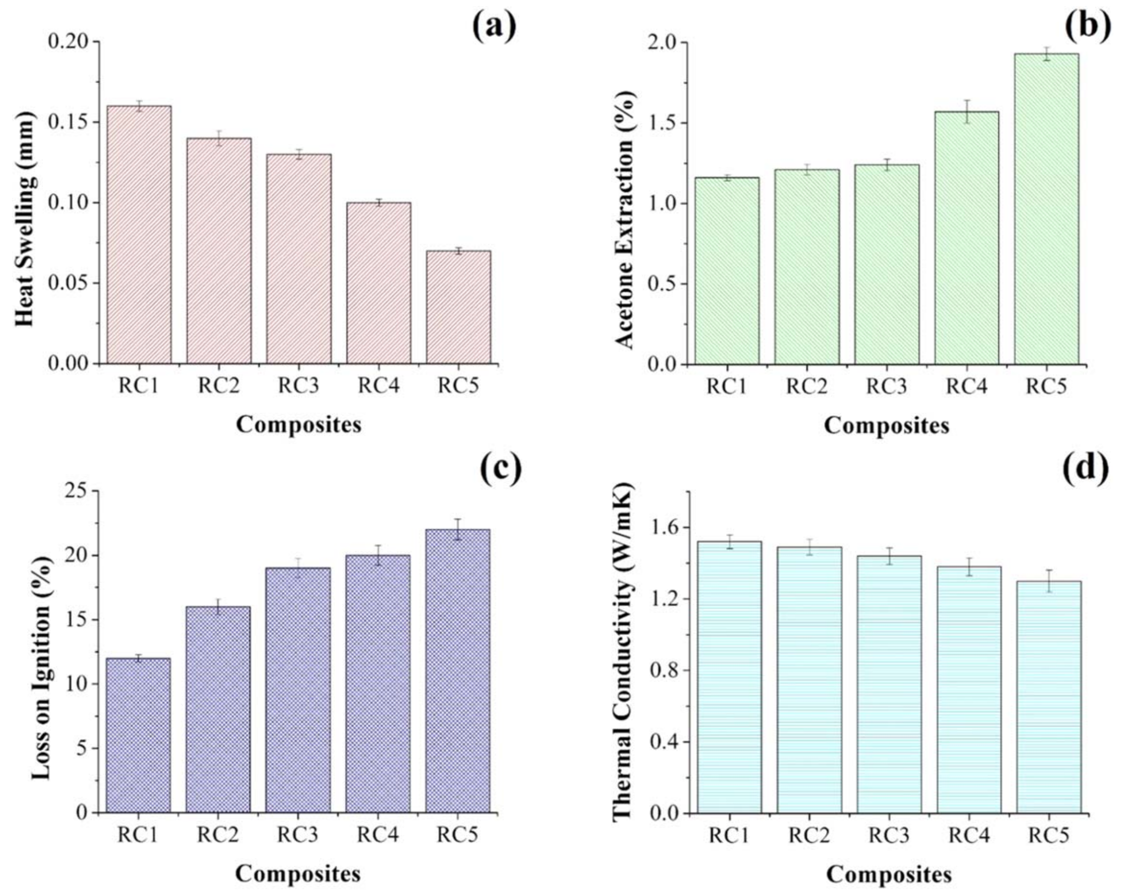

Figure 2. Developed brake friction composites (a) Heat swell; (b) Acetone extraction; (c) Loss on ignition; (d) Thermal conductivity.

The fractured surface of the developed brake friction composites were analysed using SEM to find the various characteristics at the fractured interface.

3. Results and discussions

3.1. Thermal properties

The various thermal properties of developed brake friction composites are given in figures 2(a)–(d).

3.1.1. Heat swelling

The heat swelling of friction composites showed the range from 0.07 mm to 0.16 mm and it increased with an increase in wt% of fibre content as shown in figure 2(a). Due to heat swelling, the moulded thickness control was found to poor during the removal of the partially cured friction composites from a hot press. Composite RC1 was found to more heat swelling than all other composites and this shows that fibre content has higher heat absorption capacity and follows the trend of RC5 > RC4 > RC3 > RC2 > RC1.

3.1.2. Acetone extraction

Acetone extraction is the base test to find the amount of uncured resins present in the BFCs. The composite RC1 has the higher fibre content tends to produce a lesser value of acetone extraction when compared to other composite samples as shown in figure 2(b). This indicates that the developed composite RC1 has less amount of uncured resin since it has more porosity and high fibre content, which in turn gives way for the curing heat to penetrate through the materials, thus curing the composites effectively [27]. This better curing also helps to increase the mechanical strength of the friction composites as inferred from the following section results. Acetone extraction of the friction composite follows the trend of RC5 > RC4 > RC3 > RC2 > RC1.

3.1.3. Loss of weight on ignition

Loss of weight on ignition of the friction composites at 800 °C decreases from 22 to 12 wt% with enhance in fibre amount of the composites from 5 to 25 wt% as shown in figure 2(c). This indicates that composites with lower fibre content has lesser thermally stable materials contributing to enhanced thermal degradation leading to higher weight loss. This behaviour is tandem with the literature findings of Lenin Singaravelu *et al* [28]. Loss of weight on Ignition of the friction composite follows the trend of RC5 $>$ RC4 $>$ RC3 $>$ RC2 $>$ RC1.

3.1.4. Thermal conductivity

In general, the key varying ingredients are in the fibre form exhibits more thermal conductivity than powder one. This is due to fact that, the fibre has better length-diameter (L/D) ratio than powdery ingredients. Hence, the composite RC1 has higher thermal conductivity due to better thermal conductive nature of basalt fibre (0.031–0.038 W mK^{-1}) in large contents than $BaSO_4$. Porosity has significant influence on thermal properties of the FMs as the size and distribution of internal pores can modify the thermal conductivity. Hence, composite shows better thermal conductivity and it follows the trend of RC1 $>$ RC2 $>$ RC3 $>$ RC4 $>$ RC5 as shown in figure 2(d).

3.2. Mechanical properties

The various mechanical properties of fibre reinforced hybrid friction composites are listed in figures 3(a)–(e).

3.2.1. Tensile properties

The ultimate tensile strength of the friction composites is mainly determined by wt% and strength of reinforcement fibres and the degree of bonding of fibres with phenol-formaldehyde matrix. The composite with an increased amount of fibre content (25 wt%, RC1) exhibits higher ultimate tensile strength (12.85 MPa) when subject to a tensile load, but it is found to be decreasing with decrease in fibre reinforcement. The composite with lower fibre content (5 wt%, RC5) has shown lower ultimate tensile strength of 5.96 MPa, as shown in figure 3(a). The result proves that increasing the wt% of fibre from 5 to 25 wt% results in a considerable increase in tensile strength of composites owing to its reinforcing effect. Also, in the cured phenolic matrix, the micro packing of fibres forms a cross-linked network structure which causes mechanical compaction in fibrous ingredients and also confirms effective synergism [29]. Similarly, the elongation results as shown in figure 3(b) visualizes composite having 25 wt% of fibre (RC1) is 1.15 mm and for composite RC5 (5 wt% of toughening) is 0.56 mm. Inclusion of fibres (basalt $+$ recycled aramid) in the friction composites leads to an increase the amount of elongation as expected.

In general, the mechanical properties of FMs are dependent on properties of matrix (binder), fibre and filler and interface phase. The failures in the friction composites occurred due to the debonding of fibre-matrix, pull out of fibre from the matrix, and the various degree of tensile stress at different sections when the tensile load increases. Basalt is composed of various oxides among superior strength, better heat-insulating properties and well fibre-matrix interfacial bonding [21]. Composite RC1 having higher the basalt fibre content (20 wt%) possesses the more tensile strength when compared other formulations. Also, the combinatorial properties of fibrillation, flexibility and elongation of recycled aramid fibres improved the mechanical strength of composites RC1 substantially, that is not obvious in composite RC5 resulting in easy to failure among the formulated composites. The adding of fibre content in the friction composites considerably reduced the brittleness effect; this is due to the flexibility and the elongation behaviour of the recycled aramid fibre. The failure modes on the composite occurred due to the brittleness which shows that the degree of elongation of composites remains appreciably affected by the variation of wt% of reinforcement fibre. The friction composites RC5 have only a limited range of flexibility due to the filling of powdery barites in the composite. Hence, the cracks propagated easily in composite RC5 and started to failure quickly than the composite RC1. Also the strong interfacial bonding among the fibres and matrix contributed more strength to the composite RC1 when compared to other formulations.

The phenol-formaldehyde resin in the friction composites displays weak resistance to the crack growth when it subject to external load. The reinforced fibres together with fillers strengthen the composite and enhance fibre-matrix integrity, which effectively prevents extensive scale disintegration of phenol-formaldehyde. The uniform dispersion of reinforcing fibres in the phenol-formaldehyde matrix impedes the propagation of cracks along the direction of loading. The wt% of basalt fibre in the friction composite create inadequate strength resulting in breakage of the phenol-formaldehyde matrix, thus contributing to less % of elongation is obtained in the friction composite RC5. When the friction composites are subjected to tensile load, the fibre matrix debonding or shear failures of matrix act on the composite at different modes causing fracture at different cross-sections, resulting overall failure of the composites. In friction composites, the phenol-formaldehyde matrix distributes the load to the fibres and activates the fibre matrix interface and prevents the minor cracks. Hence the composite with an increased amount of fibre (basalt $+$ recycled aramid) content (RC1, 25 wt%) protects the friction composites from cracks and defers the failure of the composite. This is probably owing to the enhanced adhesion through the matrix, excellent stiffness and strength of the reinforcement fibres and hard filler particles. Also the strong

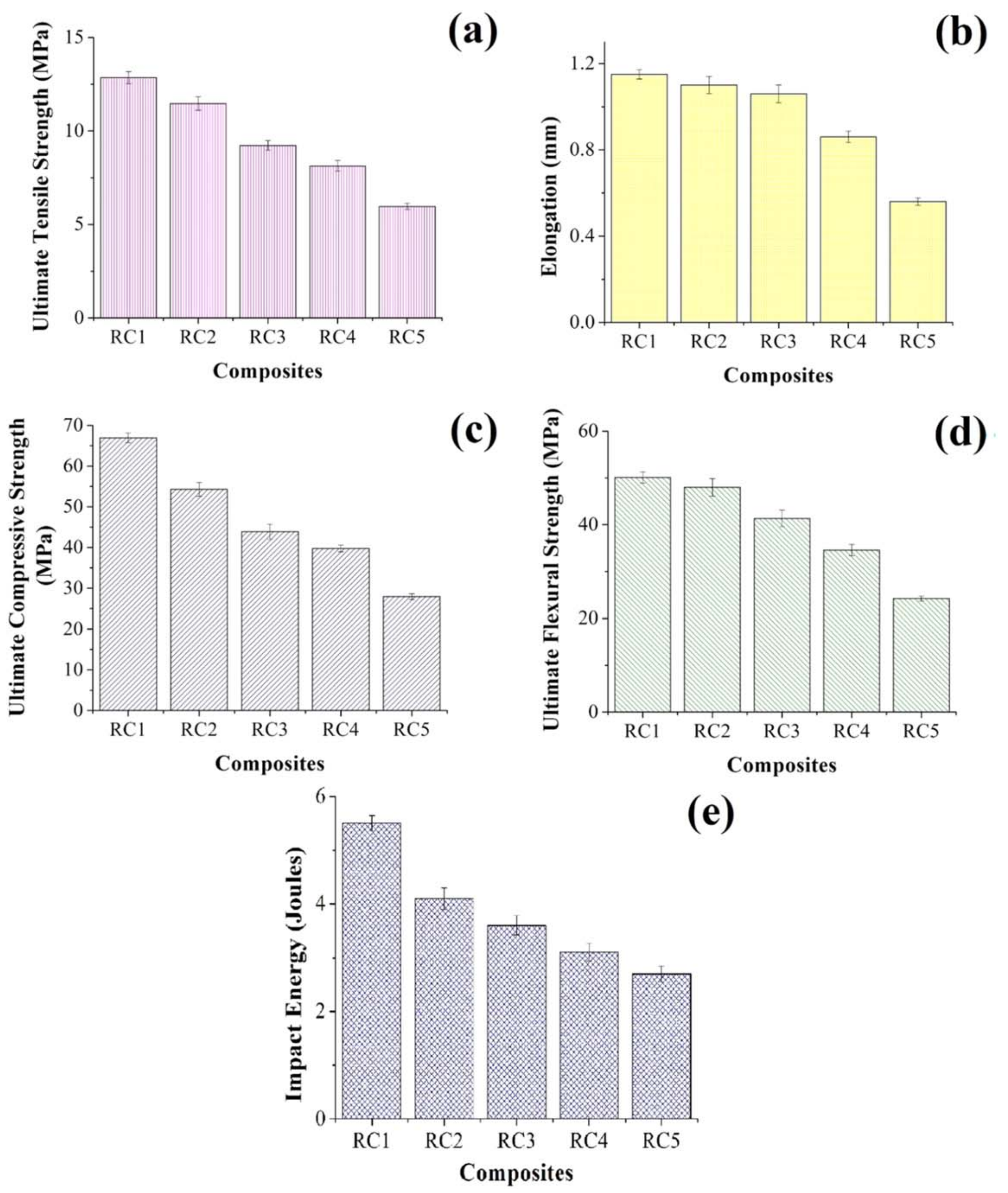

Figure 3. Developed brake friction composites (a) Ultimate tensile strength; (b) Elongation; (c) Ultimate compressive strength; (d) Ultimate flexural strength; (e) Impact energy.

interface region of fibre-matrix in composite RC1 causes increased transfer of load from the matrix to the fibre surface. Hence, the reinforcements can impart high stiffness to the phenol-formaldehyde matrix and the composite reinforced with higher wt% of fibre were found to exhibit higher tensile strength.

A brake friction composite system generally belongs to the anisotropic property (different properties at different direction) and while tensile loading, it not only does experiences along the direction of loading and contraction along the lateral direction but the shear deformation also results in crack propagation in the composites. Hence, the failure is initiated easily at the tensile side of the friction composite specimen RC5 resulting in catastrophic failure. Addition of fibre content in the friction composites enhances the interfacial strength and reduces the mobility of the phenol-formaldehyde based matrix of the friction composites. As a result, the composite RC1 shows signs of higher strength and elongation when compared to lower amount of fibre of the friction composites. Similar behaviour was seen in Satapathy & Bijwe [30], where the ultimate tensile strength of friction composites with different reinforcement fibres was found to be in the range 6.4 to 17.7 MPa. Thus the values acquired for the current investigations are in line with the previous literature.

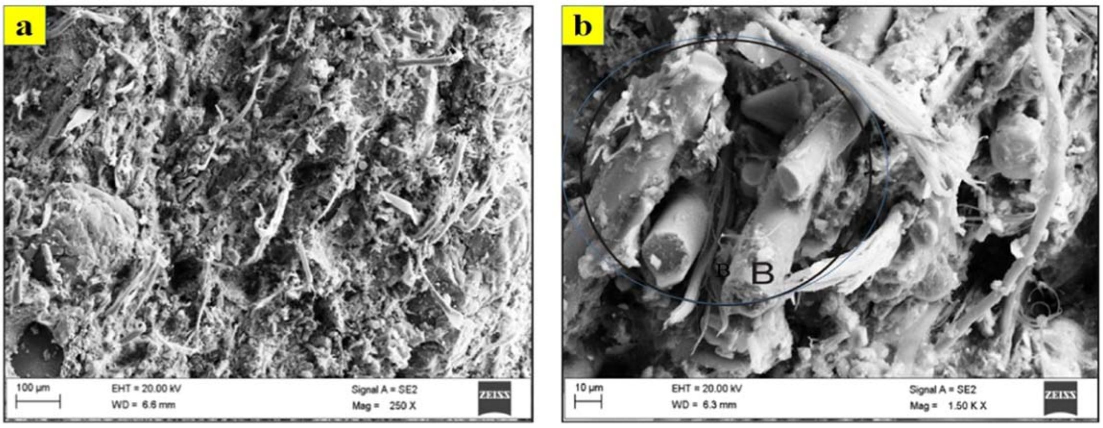

Figure 4. SEM photomicrograph of fractured composite RC1 with (a) 250× and (b) 1.50 k× magnification.

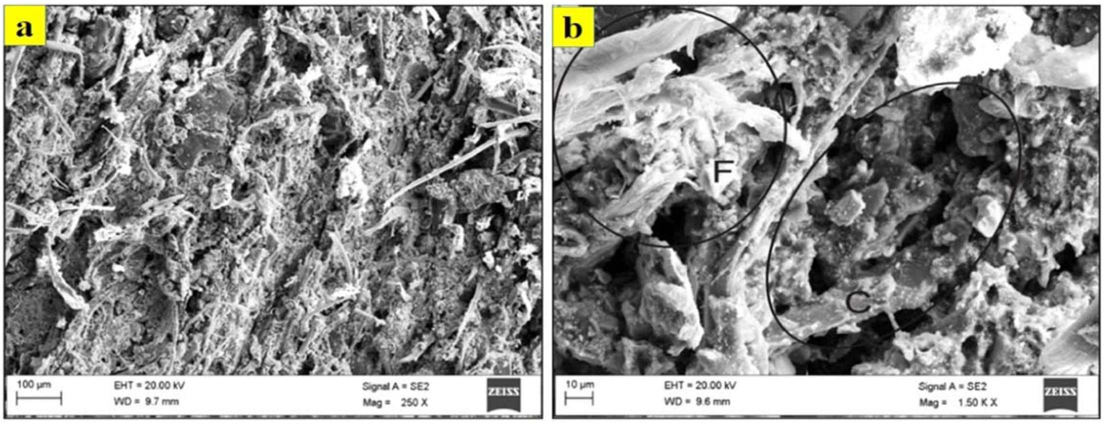

Figure 5. SEM photomicrograph of fractured composite RC3 with (a) 250× and (b) 1.50 k× magnification.

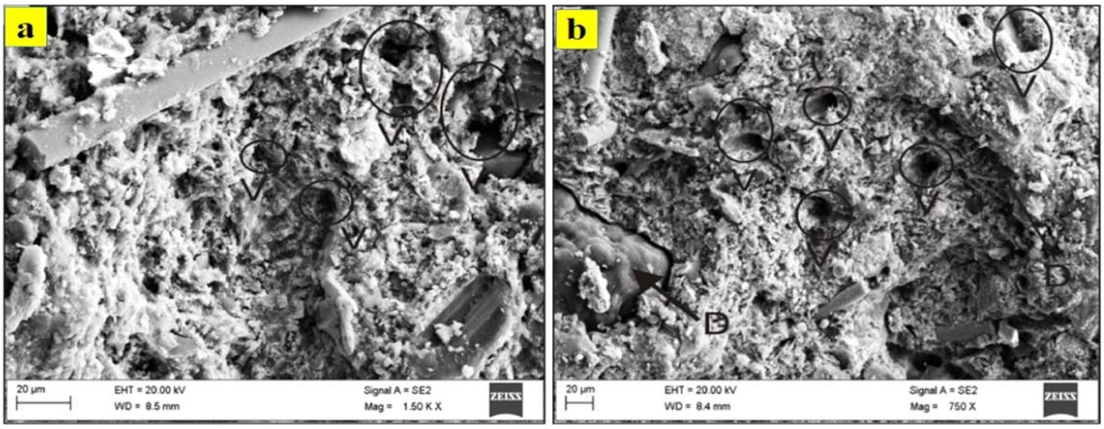

Figure 6. SEM photomicrograph of fractured composite RC5 with (a) 1.50 k× and (b) 750× magnification.

Figures 4(a), (b), 5(a), (b), 6(a), b) illustrate the SEM images of the fractured surface of composites RC1, RC3 and RC5 under tensile load in different magnification. From the figures 4(a), (b), it can be confirmed that the excellent adhesion between the fibre-matrix interfaces which shows better surface integrity in composite RC1 (25 wt% of fibre) and minimum amount of fibre pull out and fibre bonding (Marked as B) in the matrix can be noticed. This is because composite RC1 possesses better interfacial stiffness corresponding to a higher composite strength/modulus. The interfacial stiffness and adhesion strength mainly determine the ability of composite interface to transfer elastic deformation [31]. The improved adhesion is achieved between the fibres with the phenol-formaldehyde matrix due to the improved adhesive properties of fibres (basalt + recycled aramid). As expected, the addition of fibre in the friction composite RC1 was found to increase the degree of elongation before it fractured. However, deprived adhesion between fibre-matrix interface causes increased fibre breakage (marked as F) and the damage (marked as C) on matrix in a composite RC3 (15 wt% of fibre), as evident from SEM figures 5(a), (b).

The SEM images of the fractured surface of composite RC5 (5 wt% of fibre) evealed the different morphology as shown figures 6(a), (b). When compared to other composites, more the number of cracks and fibre breakage are evident from figures 6(a), (b). The poor uniform distribution of fibres in composite RC5 causes fibre pull out, fibre fracture, fibre-matrix debonding, fibre thinning (marked as T) and hard particles (marked as D) on the matrix surface are more evident in figures 5(a), (b) resulting in reduced tensile strength when compared to all other formulations. The separation between fibre and matrix is more in composite RC5 causes failure in the composites. Due to the fibre pull-out from the matrix, more voids (Marked as V) is generated RC5, as shown in figures 6(a), (b). This is because; in general, if the fibre weight ratio in the friction composites decreases below the optimal value, the load is not uniformly distributed to more fibres, resulting in weak bonding between fibre and binder (matrix), as mentioned in the SEM image. This eventually decreases in tensile strength of the hybrid friction composites. Hence, the fibre breakage, fibre pullout and fibre fracture mechanisms can be seen easily in composites RC5 and RC3 when compared to RC1.

3.2.2. Compression properties

The compression behaviour of polymer-based friction composites is of essential attention to designers as well as composite manufacturers. Compression failure is a design limiting factor of fibre reinforced polymer matrix composites. This is because, since the failure mechanism is governed by mainly compressive stresses in most of the circumstances. During braking, the compressive stresses are generated in the friction composite system, either by direct compressive loading and/or by bending or impact loading. The composites should have high compressive strength and should not fail under the applied braking pressure. In the case of commercial friction material, the maximum compressive strength was 110 MPa [3]. In general, the compressive strength in the composites is determined by fibre misalignment and plastic shear deformation in the matrix [32]. The fibre crushing is the dominant failure mechanism which generates stresses in the polymer-based friction composite system. Also, the fibre crushing causes shear instability and shear deformation of the fibre associated with phenol-formaldehyde matrix system.

Usually the reinforcement fibres in brake friction composite formulation are stiff and robust. Also, the phenol-formaldehyde matrix has a much lower mechanical strength and a higher level of toughness as compared to reinforcement fibres in order to provide the composite with in-plane strength and flexibility. In the hybrid friction composite system, the composite with an increased amount of fibre content (25 wt%, RC1) resists the stress generation due to its higher degree of stiff and robust nature of the reinforcement fibres (basalt + aramid). Further, the increased amount of fibres in the friction composites increases the compressive strength by neglecting the fibre crushing failure and retaining its antistrophic property firmly. Hence, the composite with lower amount of fibre content (RC5, 5 wt%), only small compressive stress is required for propagation of crack and shear bonding which is due to lower wt% of fibre in this system as shown in figure 3(c). The increased amount of reinforcements in composite brake pad enlarges the compactness of composites. Due to material compactness, the higher strength is maintained in composite brake pad [33]. Hence the ultimate compressive strength of the brake friction composite increases from 27.92 to 66.96 MPa with addition of wt% of fibre content from 5 to 25%.

3.2.3. Flexural properties

In general, the flexural strength of the composites is a capability of the material to endure bending force applied perpendicular to its longitudinal axis. The developed stresses owing to flexural load are a combined effect of compressive and tensile stress. The transfer of stress in the fibre-matrix determines the flexural strength of the composite system. The flexural strength of the friction composite is essential when the composite subjected bending applications. From the figure 3(d) it is confirmed that composite having higher amount fibre content (RC1, 25 wt%) posses superior flexural strength (50.09 MPa) when compared to other composites. The excellent mechanical properties of basalt fibre and fibrillation, flexibility and elongation properties of recycled aramid fibre increase the stress transfer between the fibre-matrix and make the stable fibre-matrix interface to enhance the flexural strength of composite RC1. Also, the modulus of the fibres is superior to the neat phenol-formaldehyde matrix. The higher amount of fibre reinforcement in hybrid friction composite RC1 enhances the bending resistance and resists the bending load and improves the flexural strength of the composites. Further, the inclusion of filler content in the friction composites along with carbon black powders increases the amount of internal reaction and reduces the flexural strength, indicating more damage to the fibre. However, the filler content significantly enhances the composites wear resistance. Hence, the flexural strength follows the trend of RC1 > RC2 > RC3 > RC4 > RC5.

3.2.4. Impact properties

The impact test is used to determine the amount of impact energy of the material required to oppose the rupture under sudden load at high speed. Impact energy is interconnected to the toughness of the composite specimen. Usually, the incorporation of fibre reduces the void content of the friction composite significantly. When the polymer-based composite materials are subject to sudden loading conditions, energy abortion of composites is mainly determined by plastic deformation of matrix material, fibre-matrix interface debonding and the fracture of reinforcement fibres. The fibres (basalt + recycled aramid) play a crucial role in determining the impact energy by resisting the crack propagation of the friction composites and acting as a load transfer medium to the phenol-formaldehyde matrix. Composite with a higher the fibre content shows better impact energy and varies from 0.151 to 0.451 Joules with an increase in fibre content from 5 wt% (RC5) to 25 wt% (RC1) as shown in figure 3(e). The gradual increase in impact energy is due to fracture strength of fibres (basalt +recycled aramid) and compression pressure which eliminates void content in the friction composites. The fibre length has a significant effect on enhancing the impact strength to withstand sudden load and also determines the impact mechanism of the friction composites. During impact, when the impact energy exceeds the fibre strength, the fracture occurs at the fibre and the fibre transfers the fracture thorough out the composites. The short basalt fibre along with recycled aramid fibre may dissipate the impact load effectively by maintaining its strength in the friction composites. Thus, the phenomenon absorption of impact energy becomes prominent composite RC1 and transfers the fracture easily throughout composites and withstands a higher load by maintaining impact energy when compared to other formulations. In similar investigations, Botev *et al* [34] examined the mechanical properties of basalt fibre-reinforced polypropylene-based composites and concluded that the addition of basalt fibre improves the mechanical behaviour of the composites considerably.

From the results attained, it may be potential to state that adding basalt fibre along with recycled aramid fibre get better the mechanical and thermal properties of the brake friction composites considerably. The future scope of the current study is to analyse the composites for its dynamic mechanical properties and tribological properties using full scale dynamometer.

4. Conclusions

Brake friction composites were developed using recycled basalt and aramid fibres in combination with parental ingredients and analyzed for its thermal and mechanical properties as per industrial standards. Based on the test results, the following conclusions were drawn.

- The heat swelling of friction composites increased with the addition of fibre amount from 5 to 25 wt%.
- The acetone extraction and loss of weight on ignition of the composite samples decreases with an increase in wt% of the fibre content
- Thermal conductivity of the composites showed better performances upon fibre inclusion with 1.52 $\mathrm{W\ mK^{-1}}$.
- The mechanical properties (tensile strength, compression, flexural and impact) of the composites increased with an addition of reinforcement fibres from 5 to 25 wt%.
- The fibre pullout, fibre thinning and generation of more voids decreased the tensile strength of lower wt% of composite (RC5, 5 wt%) were confirmed from the SEM studies.
- The higher fibre content (25 wt%) in the friction composites imparted better bending resistance and impact strength to the brake friction composites.

Thus recycled basalt and aramid fibres can be effectively used as fibre reinforcement in the development of non-asbestos based brake friction composites.

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