Synergistic Influence of Banana Pseudo Stem Fibre and Synthetic Fibre on Mechanical, Thermal Stability and Tribological Properties of Epoxy-Based Composites

Abstract

In this work,the synergistic influenceof Banana Pseudo Stem Fibre (BPSF) and synthetic fibre on mechanical, thermal stability and tribological characteristics ofepoxy-based composites wasexamined. The three synthetic fibres used in this study were Kevlar (KK), glass (GG) and carbon (CC). Hand lay-up lamination method was used to develop unhybridised and hybridised epoxy composites. The unhybridised epoxy composite reinforced with BPSF was denoted as BBBB. The hybrid of BPSF with KK, GG and CC were designated as BBKK, BBGG, and BBCC, respectively.Mechanical, thermal stability and wear tests were carried out according to ASTM standards. Microstructure evolution was examined withSEM NIXRN (Model 541).The BBCCexhibited higher tensile strengthand compressive strength (159.11, 65.21 MPa) when compared to BBGG (141.11, 58.21 MPa), BBKK (144.27, 55.51 MPa), and BBBB (109.38, 52.77 MPa), respectively.The improved hardness in the hybridised samples, BBCC (109.25 BHN), BBKK (89.77 BHN), and BBGG (82.23 BHN), are attributed to the filling of BPSF pores with synthetic reinforcements, when comparedto the unhybridised BBBB (78.12 BHN).The BBCC demonstrated highestthermal stability, with a mass residue of 18.00 %. The sample also demonstrated the lowest wear under the tested loads. The microstructures revealed a finely dispersed fibresand better adherence in the matrix as compared to others. The hybridised samples demonstrated better properties compared to the unhybridised. The BBCC, a combination of 2-layer configuration of BPSF and CC exhibited the best mechanical, thermal stability and tribological characteristics.

Keywords: Epoxy-based composites, Reinforcements, Thermal stability, Tribological characteristics, Microstructure evolution

1. Introduction

The growing researchers’ interest in composite materials development and characterisations for structural applications cannot be overemphasised. Based on the matrix, composites are classified as Metal Matrix Composites (MMCs), Polymer Matrix Composites (PMCs) and Ceramic Matrix Composites (CMCs). The PMCs have attracted considerable attention as engineering materials due to their low cost,lightness and corrosion resistance properties. However, PMCs suffer failure under low stress thus, limiting their applications in machine components requiring high strength, thermal resistance and low wear rate (Gangil *et al.*, 2020; Khatkar, 2023). To overcome these limitations and enhance their suitability, synthetic fibres can be incorporated into the composite. Among the available methods for fabrication of PMCs, hand lay-up is commonly used due to its simplicity and cost-effectiveness (Devaganesh *et al.*, 2020; Jayendra *et al.*, 2020; Zuo *et al.*, 2021).The researchers opted for epoxy as the base resin due to its versatility, strength, corrosion resistance, cost-effectiveness, and durability, surpassing other polymers and solid metals. It is also relatively cheaper than metal alloys. By incorporating materials with superior strength and utilising high-strength primary and secondary reinforcements in the polymer, a composite is created that lies between the strength of alloys and ceramic reinforcing materials (Badyankal *et al.*, 2021; Balda *et al.*, 2021; Hamidon *et al.*, 2019).

Combining two or more natural fibres in hybridisation offers several advantages, including improved mechanical properties, renewability, cost-effectiveness, and recyclability. The performance of the resulting composite depends on the characteristics of each hybrid fibre. For example, Banana Pseudo stem(BPS) fibre's low density benefits lightweight hockey equipment, but its brittleness restricts its applications in requiring ductility(Kumar &Mohamed, 2018). Enhancing ductility can be achieved by combining natural fibres such as coir and flax with BPS fibre. Successful hybridisation with natural fibres requires adequate knowledge of the individual fibre constituents, its volume, interaction with the matrix, orientation, and treatment with chemical. Research on mechanical properties has demonstrated that a randomly oriented composite of snake grass, banana, and coir fibres exhibits superior tensile and flexural strength compared to individual fibre composites(Balaji *et al.*, 2021). Similarly, investigating the tribological, thermal, and mechanical effects of banana and jute fiber epoxy composites reveals that the hybrid composites outperform the individual composites(Rajesh *et al.*, 2020).

While natural fibres offer advantages such as cost-effectiveness, renewability, and biodegradability, hybridisation with synthetic fibres addresses the limitations of natural fibres in engineering applications, including low density, hydrophilicity, and inadequate mechanical and thermal properties in polymer composites(Soraisham *et al.*, 2021). Combining synthetic fibres like carbon, glass, aramid, and Kepler fibres with natural fibres such as sisal, jute, pineapple, cotton, and banana fibres in PMCs yielded polymer composites with well-balanced and enhanced strength, thermal properties, and wider applications. Due to the hydrophilic nature of natural fibres, they tend to absorb moisture and expand in both thickness and length. Therefore, improving the fibre structure through chemical treatment before hybridisation with synthetic fibres is recommended as it proves more effective than using untreated natural fibres. The inclusion of synthetic fibres mitigates the hydrophilic effect of natural fibres by occupying space that would contribute to hydrophilicity (Khare *et al.*, 2021; Paz *et al.*, 2020; Tay *et al.*, 2021).

Choosing the appropriate processing technique enhances the compatibility between the fibre and matrix, leading to improved mechanical strength that can partially or wholly replace synthetic fibres in applications requiring higher strength.In contrast to fully synthetic fibre composites, the utilisation of natural-synthetic fibre hybrid composites offers a solution to mitigate environmental pollution arising from the use of non-renewable synthetic fibres (Safri *et al.*, 2018). It has been consistently observed that combining high-strength synthetic fibres with natural fibres leads to enhanced impact strength, even when employing low-strength resins(Alavudeen *et al.*, 2015). However, it is important to note that the presence of more than two fibres does not necessarily result in increased strength for hybrid composites, contrary to the findings reported byBhoopathi *et al.* (2015). The individual properties of the fibres and their compatibilities with the matrix material are critical factors influencing the overall strength. For marine applications, Dinesh *et al.* (2020) conducted a comparative study on the strength of epoxy composites incorporating banana bract/Kevlar, palm/Kevlar, and banana bract/palm/Kevlar fibres. The composite containing banana bract/Kevlar demonstrated the lowest weight, water absorption, and highest mechanical properties. However, the banana bract/palm/Kevlar fibre epoxy composite exhibited reduced tensile properties due to its high water absorption, rendering it unsuitable for marine applications.

Despite the abundant literature on polymer hybrid composites, there is dearth of information on research reports that explored the integration of Kevlar, glass, and carbon fibres with banana pseudo fibre hybrid composites. Therefore, the aim of this research is to develop and investigate BPSF/synthetic fibre reinforced epoxy-based composites. The BPSF layers were consistently maintained at two, while the layers of synthetic fibres (carbon, Kevlar, and glass) were also kept constant at two. Mechanical, thermal stability and tribological characteristics of epoxy-based composites derived from BPSF and the three selected synthetic were characterised.

2. Materials and methodology

2.1. Materials

In the experiment, a composition of epoxy and hardener was prepared in a 2:1 ratio to fulfill the roles of resin and binder, respectively. The woven carbon, glass, and Kevlar fibres were obtained from Chatex Suppliers, a supplier located in Lagos, Nigeria. The specific banana variety utilised was the Giant Cavendish, acquired from NIHORT in Nigeria. The fibres were manually extracted from BPS ribbons. To achieve a fine particle size, coconut shell ash (CSA) was obtained and pulverized. The fibres underwent a chemical treatment using sodium hydroxide, while the curing temperature was carefully controlled and adjusted using an oven.The materials required for this composite preparation is presented in Figure 1.

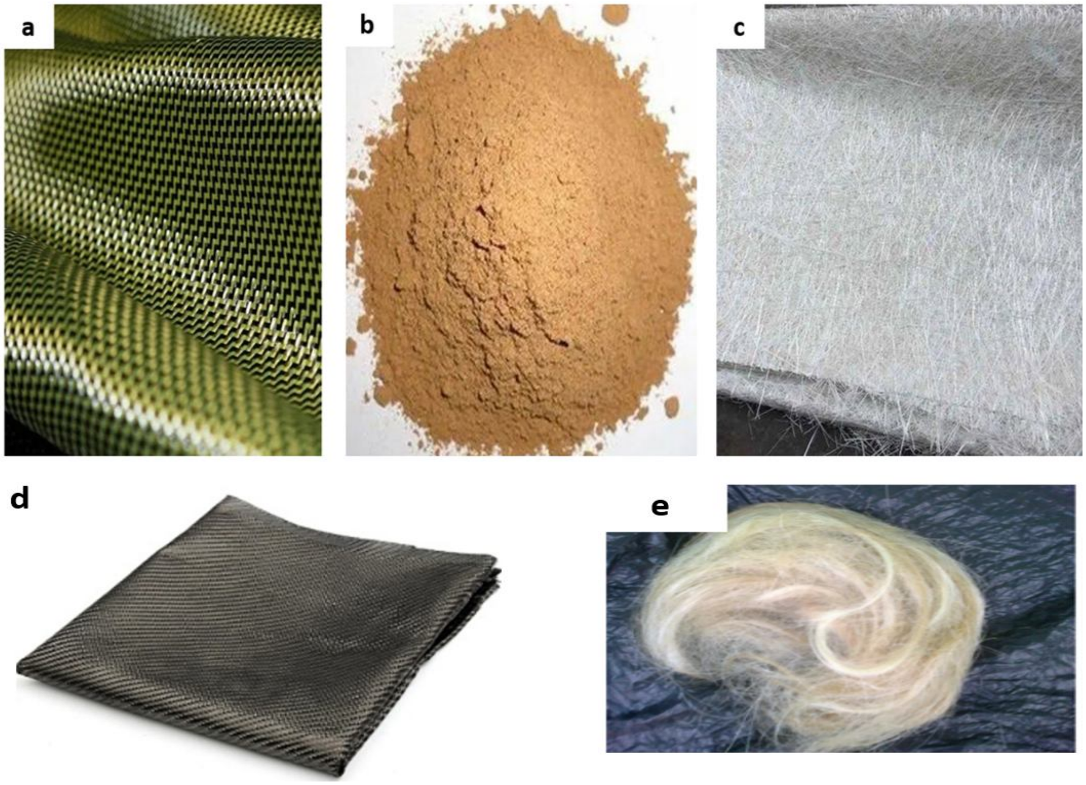

Figure 1: Materials for composite samples: (a) Kevlar fibre (b) Coconut Ash Shell (c) Glass fibre (d) Carbon fibre (e) BPSF.

2.2. Fabrication

The composites were produced using the hand layup method, where a combination of resin and reinforcement fibre was shaped and solidified using a mould. To ensure a crack-free and smooth surface upon mould removal, a polyethylene sheet coated with releasing wax was utilised. The flat metallic mould was evenly coated with epoxy resin using a brush, and a BPSF fibre sheet was placed inside the mould. Rolling was employed to thoroughly saturate the fibre with resin. This process was repeated, adding layers of carbon fibre until reaching four layers. The same procedure was applied to Kevlar and glass fibres. Two layers of BPSF were consistently integrated throughout the manufacturing process. To remove excess resin and air bubbles, a dead load was applied to the specimen, which was then cured within a temperature range of 30 °C. The unhybridised epoxy composite reinforced with BPSF was denoted as BBBB. The hybrid of BPSF with KK, GG and CC were designated as BBKK, BBGG, and BBCC, respectively.

3. Methodology

3.1. Tensile and compressive test

The samples were placed in the grips of a universal test machine, with a specific grip separation which was pulled until failure. According to D638, dumbbell shape specimen is needed for polymer reinforced composite testing.On the other hand, a compression test was performed by placing the sample into two plates in which force was applied to the samples. Deformation against load was monitored as a result of the samples being compressed.

3.2. Hardness test

Material hardness refers to the resistance of a material against penetration. The measurement of shore D hardness relies on assessing the strength required for a needle to penetrate the test material under specific spring loads. These test results enable the comparison of composite material hardness. The samples passed the Brinell hardness test and were produced in compliance with ASTM E10 standard.

3.3. Thermogravimetric analysis

To characterise thermal stability offibre samples derived from the pseudo stem of bananas, Thermogravimetric Analysis (TGA) was carried with the aid of a TGA/MSS 773 Nester Tolder apparatus. Thermal analysis was conducted on the unhybridised and unhybridised compositesamples within a temperature range of 30 to 550°C, employing a heating rate of 150°C per minute. The sample weights varied between 5 and 10 milligrams. A total of four samples were examined, and their final mass residue was recorded.

3.4. Wear Properties

In order to evaluate the durability characteristics of the developed composites,wear tests were conducted based on ASTM D1242 using the NH-56KJ apparatus. The apparatus consisted of a setup involving a pin on a disc. The cylindrical disc was exposed to standard operating conditions, covering a distance of 12 meters and possessing a diameter of 10 millimeters. The track radius and velocity were adjusted to 1 meter per second, resulting in an overall sliding distance of approximately 1000 meters. Various forces, including 10, 20, and 30 Newtons, were applied at speeds of 1.5 and 3.0 meters per second. Throughout the application of force, careful monitoring of the wear rate, percentage weight loss, and coefficient of friction was conducted.

3.5. Scanning Electron Microscopy

The SEM NIXRN (Model 541) microscope was employed to examine evolved microstructures of the developed composites. This particular microscope operated at a voltage of 12 kV and had a working distance of 3 mm. To ensure the fibre's conductivity and suitability for analysis, a layer of gold with a thickness of approximately 20 nm was applied.

4. Results and Discussion

4.1. Mechanical properties

4.1.1. Tensile strength

Figure2 illustrates the comparison between the impact of synthetic reinforcements and non-hybridised banana fibres composites on the tensile and yield strength of epoxy composites. The hybrid composites demonstrated superior tensile strength, exhibiting an increase ranging from 22.41%, 24.45% and 29.58 %, respectively, for BBGG, BBKK and BBCC compared to BBBBsample (109.44 MPa). This enhancement in tensile strength can be attributed to the robust bonding between the polymer resins and reinforcing materials. Additionally, factors like defects, type and quantity of reinforcement, and the processing method contribute to the overall increase in tensile strength. In a study byOyewo *et al.* (2022), it was found that the incorporation of synthetic reinforcements in natural fibre composites led to 40% increase in tensile strength. Similarly, Gupta *et al.* (2021) reported a 33% increase in the kenaf/carbon fibre composite compared to non-hybridised samples. It was also reported that incorporating up to 10% carbon fibre content in a hybrid composite resulted in improved tensile strength and elongation. Thus, the addition of hybrid synthetic fibers proportionally enhances the tensile strength of the composite. Among the epoxy-based composites tested, BBCC exhibited the highest strength, followed by BBKK and BBGG, while BBBB had the lowest tensile strength due to the lower density of banana fibre. The utilisation of synthetic fibres in composites offers advantages due to their hydrophobic nature, addressing one of the major challenges in purely natural fibre reinforced epoxy-based composites.

Previous studies have demonstrated similar increases in tensile strength when glass, carbon, or kenaf fibre were incorporated into composites (Gangil *et al.*, 2020; Gideon & Atalie, 2022; Ramesh *et al.*, 2017). Notably, the highest tensile strength displayed by BBCC, 155.42 MPa, as compared to the other samples can be attributed to the absence of pore agglomeration and voids in the reinforcing carbon fibers. Venkatasudhahar *et al.* (2020)observed a correlation between the increase in carbon fibre content and the improvement in tensile strength of hybrid composites (kenaf/carbon epoxy composite).

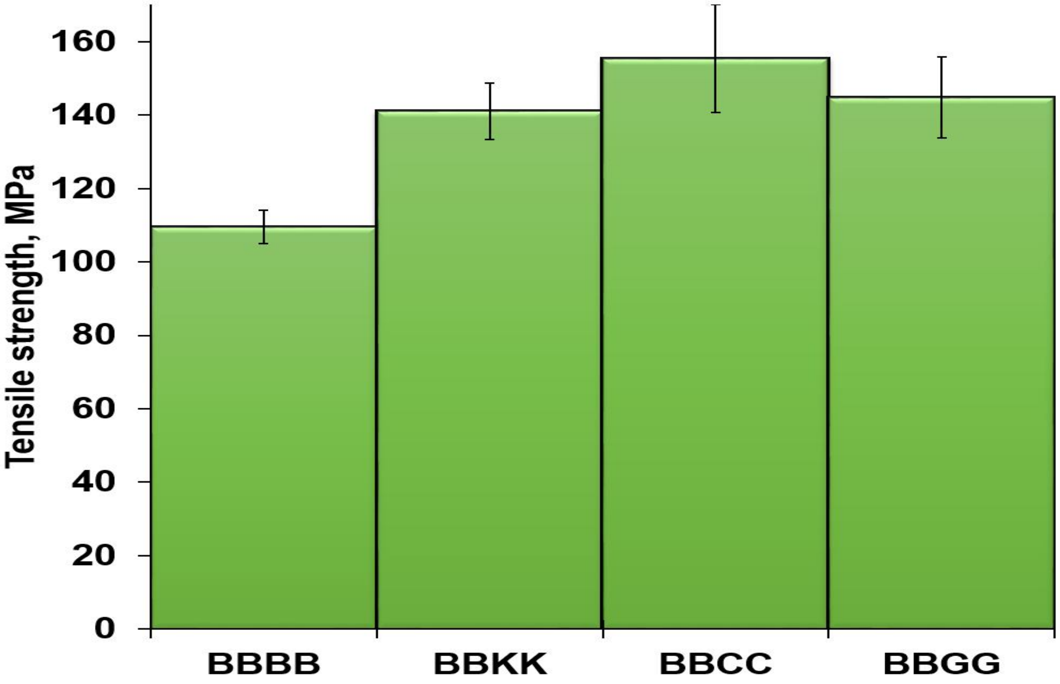

Figure2: Tensile properties of hybrid composites

4.1.2. Compressive strength

The compressive test was conducted on four samples following ASTM guidelines at room temperature. Figure 3 illustrates the impact of hybridising carbon, glass, and Kevlar fibres. Similar to the tensile strength, the compressive strength showed a proportional increase with the addition of synthetic fibres. Hybridisation effect of synthetic fibres was more pronounced in BBCC as compared to other samples. This could be attributed to carbon fibre being less susceptible to delamination compared to other fibres. In summary, all the hybridised composites exhibited higher compression strength compared to the unhybridised composite.

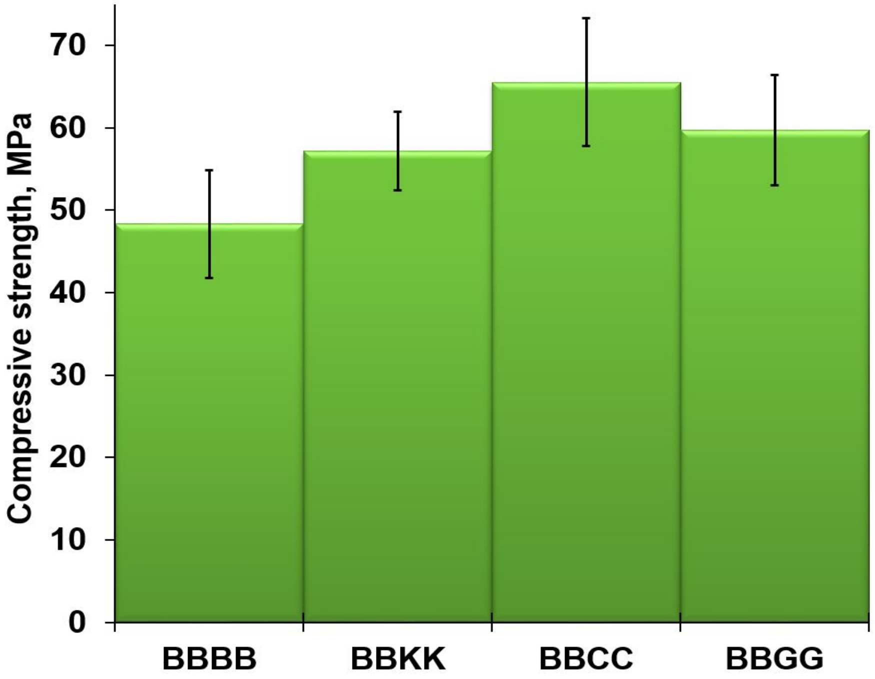

Figure 3: Compressive strength of epoxy-based composites

4.1.3. Hardness test

Figure 4 presents the hardness for both hybrid and unhybridised composite samples. The inclusion of different synthetic fibres resulted in increase of the composite's hardness. The improved hardness observed in the hybridised samples, specifically BBCC (109.25 BHN), BBKK (89.77 BHN), and BBGG (82.23 BHN), can be attributed to the filling of BPSF pores with synthetic reinforcements, contrary to the unhybridised BBBB (78.12 BHN). Previous research studies, such as those conducted by Sutradhar *et al.* (2018), Khare *et al.* (2021) and Nayim *et al.* (2020), have also reported similar hardness enhancements through the incorporation of rigid particles like carbon, glass fiber, and silica carbide. The hardness of natural fibre reinforced composites was notably lower than that of composites reinforced with synthetic fibres, as well as monolithic metals and alloys. However, by hybridising synthetic reinforcements with natural fibres, the resulting product demonstrates an increase in hardness, enabling it to compete with metallic alloys. Other researchers have documented the hardness improvement resulting from the incorporation of harder reinforcements (Kenned *et al.*, 2020; Vimalanathan *et al.*, 2021). Conversely, a decrease in hardness has been observed when employing soft reinforcements, as reported by Anbupalani *et al.* (2020). Similarly, other studies have indicated that the addition of soft reinforcements, such as rice husk ash, can reduce the hardness of a composite (Nayim *et al.*, 2020; Sutradhar *et al.*, 2018; Vishnu Vardhini *et al.*, 2018). While it is advisable to consider cost reduction and utilise renewable and biodegradable reinforcements, careful selection of agro wastes is essential to avoid compromising the intended hardness of the resulting composites.

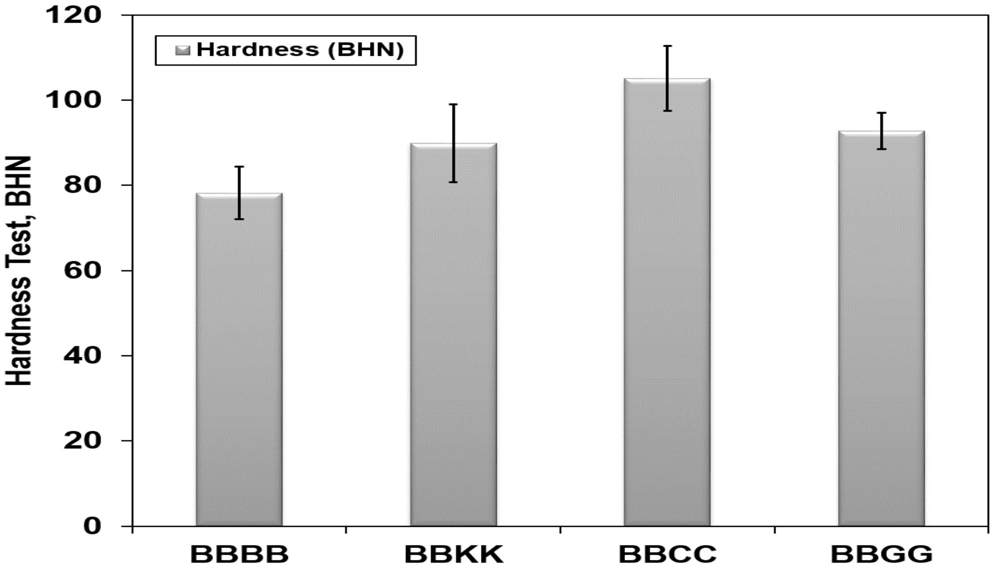

Figure 4: Hardness test of epoxy-based composites

4.2. Thermogravimetric analysis

The TGA curve is depicted inFigure 5, providing valuable insights into the thermal stability of the composite samples. Throughout all stages up to 550 °C, the composite exhibited significant weight reduction. Table 1 displays the mass residue of the samples as well as various degradation temperature from the TGA curve. This table summarises the degradation stages observed in the TGA curve, namely initial, halfway, and complete degradation.

During the initial stage, moisture loss was observed consistently across all samples. The composite experienced a notable weight reduction of approximately 5% during the initial decomposition stage. As the temperature increased, the decomposition rate accelerated, with the halfway decomposition temperature recorded at 325 °C. On average, the final decomposition temperature for all samples fell within the range of 394 °C. At this stage, the cementious lignin was broken down, and all the BPSF was decomposed. However, the carbon, Kevlar, and glass fibre hybrid composite samples did not fully degrade at this temperature. This can be attributed to the saturation of the hydrophobic site, inherent in natural fibres, with synthetic fibres.

On the other hand,Figure 6 depicts the mass residual of the samples after total degradation process, representing the percentage of mass remaining after reaching the final degradation temperature of 550 °C. The results indicate that the hybridised composites exhibited higher thermal stability compared to the non-hybridised BBBB composite. Among the hybridised samples, BBCC demonstrated the highest thermal stability, with a mass residue of 18.00 %, closely followed by BBKK (13.23 %) and BBGG (11.11 %). BBCC was 17.63 % higher than unhybridised BBBB sample. In addition to improved thermal stability, higher mass residue offers advantages such as reduced production and lower conductivity of burning materials.In line with these observations, Vijaya -Kumar *et al.* (2019), Kenned *et al.* (2020)andVigneshwaran *et al.* (2020)reported that different materials compositions contributeto an increase in residual weight.

Table 1: The thermal degradation temperature of composite samples

Samples	SDT (^{0}C)	MDT (^{0}C)	TDT (^{0}C)	% Mass residue
BBBB	204	325	373	6.67
BBCC	206	312	379	18.00
BBKK	218	328	382	13.23
BBGG	216	320	388	11.11

Where SDT, MDT and TDT are the Starting Decomposition Temperature, Middle Decomposition Temperature and Total Decomposition Temperature, respectively.

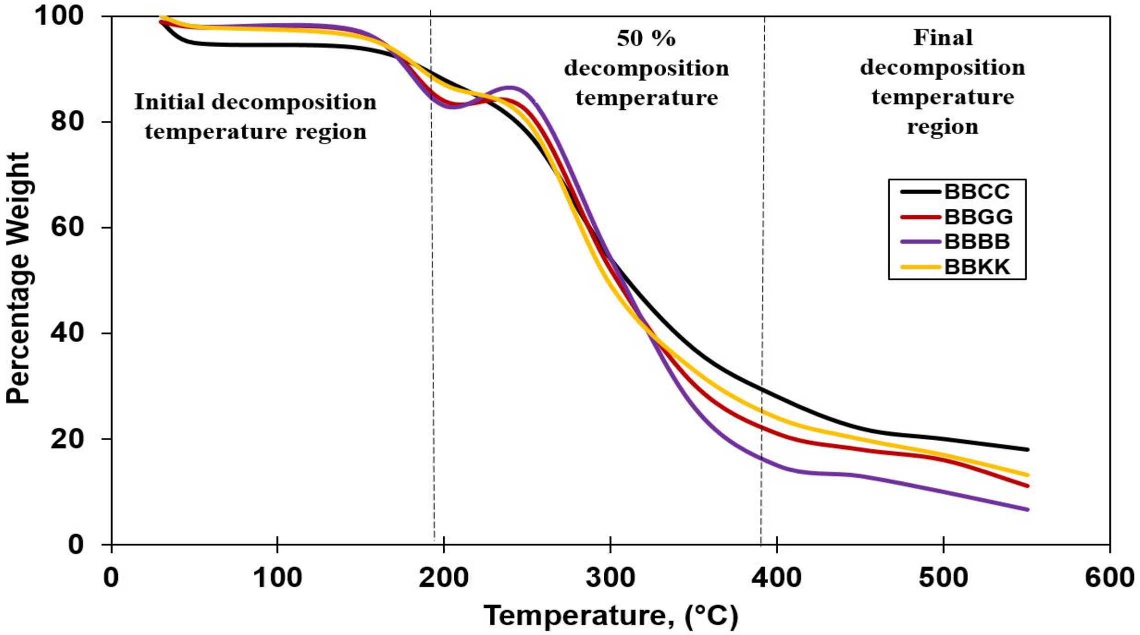

Figure 5: TGA curve of the composite samples

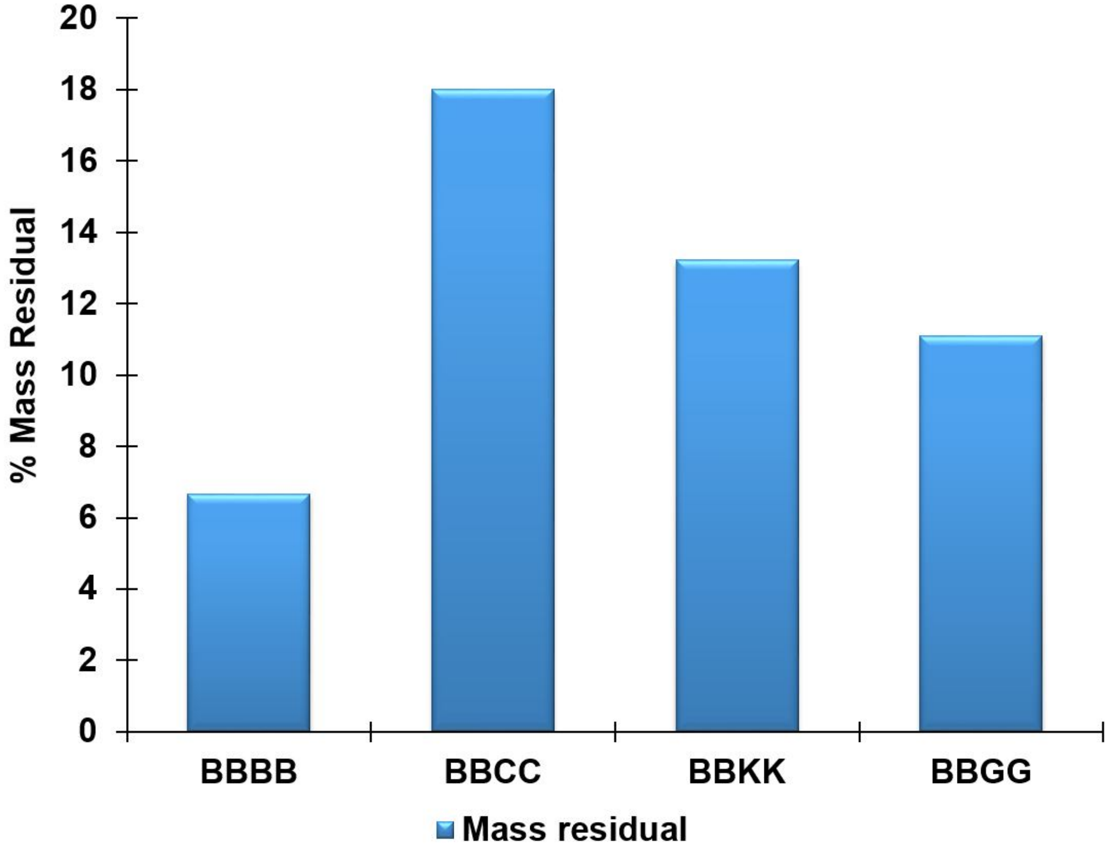

Figure 6: Percentage mass residual of epoxy composite samples

4.3. Wear test

4.3.1. Specific wear rate

The specific wear rates for velocities of 1.5 m/s and 3.0 m/s can be observed in Figure 7 and Figure 8, respectively. The amount of wear experienced by a material depends on factors such as applied load, sliding velocity, and distance. The samples were prepared in accordance with ASTM D1242 guidelines. Various conditions, including load (10, 20, 30 N), sliding speed (15 and 3.0 m/s), and a fixed distance of 1000 m, were tested (Bachchan *et al.*, 2021). The unhybridised sample exhibited the highest wear rates, measuring 0.215, 0.32, and 0.341 g for 10, 20, and 30 N, respectively. However, the wear rates decreased with the inclusion of synthetic reinforcements in the hybridised samples. Consequently, BBCC demonstrated the lowest wear among all load applications, followed by BBGG and BBKK. These findings clearly indicate that hybridisation significantly reduced the wear rates. Additionally, an increase in sliding speed led to an increase in the rate of wear. Biradar *et al.* (2020)'s report confirmed that both load and sliding speed played a substantial role in the wear rates. The addition of 2 wt. % CSA particles resulted in a harder sample. Vijaya Kumar *et al.* (2019) reported that as a composite material becomes harder, its wear rate decreases.

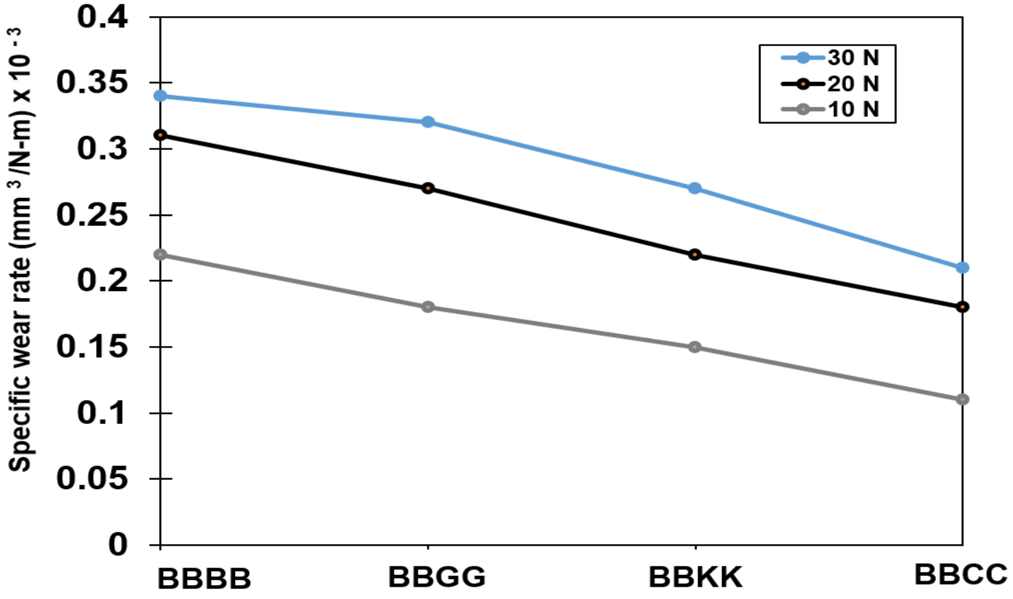

Figure 7: Specific wear resistance of the samples at 1.5 m/s for 10, 20, 30 N.

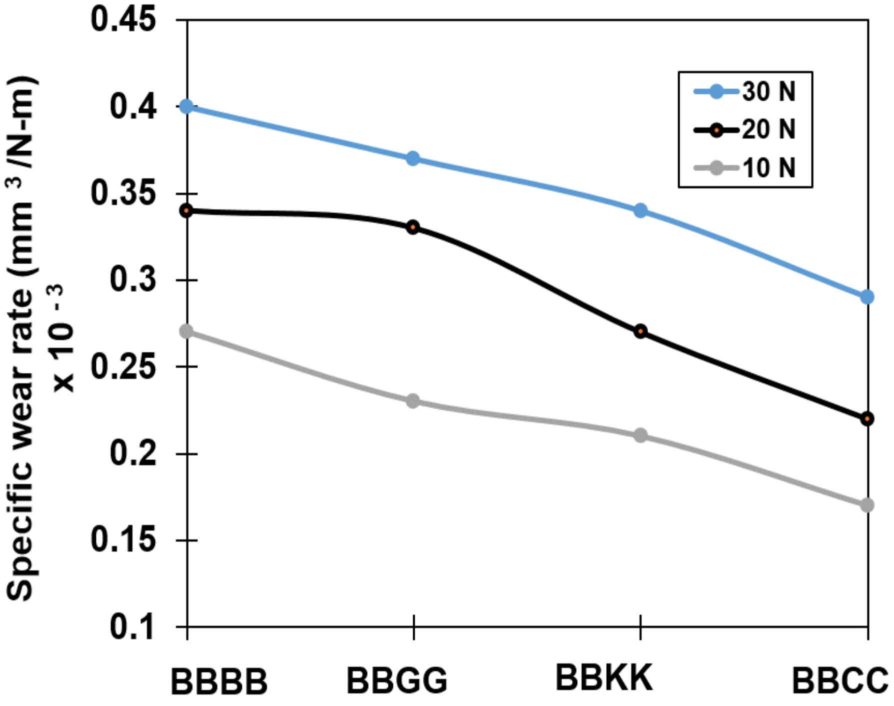

Figure 8: Specific wear resistance of the samples at 3.0 m/s for 10, 20, and 30 N.

4.3.2. Loss of weight

The impact of reinforcement and hybridisation on weight reduction, attributed to the introduction of synthetic reinforcements, is depicted in Figure 9**.**Similarly,Figure 10presents the loss of weight for 3.0 m/s sliding speed at 10, 20 and 30N for all samples. The weight loss varied between hybrid and non-hybrid composite materials. The findings indicate that as the applied loads increased by 10, 20, and 30 N, the weight loss in the composites gradually decreased. Both speed and load have a significant influence on the extent of wear loss. When higher combinations of load and speed are applied, the wear rate and weight loss increase accordingly(Bachchan *et al.*, 2021; Biradar *et al.*, 2020). In general, the results demonstrate that BBCC, particularly when carbon fibre is utilised as a synthetic reinforcement, exhibited the lowest weight loss among the developed composites in this study. However, incorporating hard reinforcement particles such as CSA enhanced hardness and reduced weight loss in polymer composites(Zhen-Yu *et al.*, 2019).

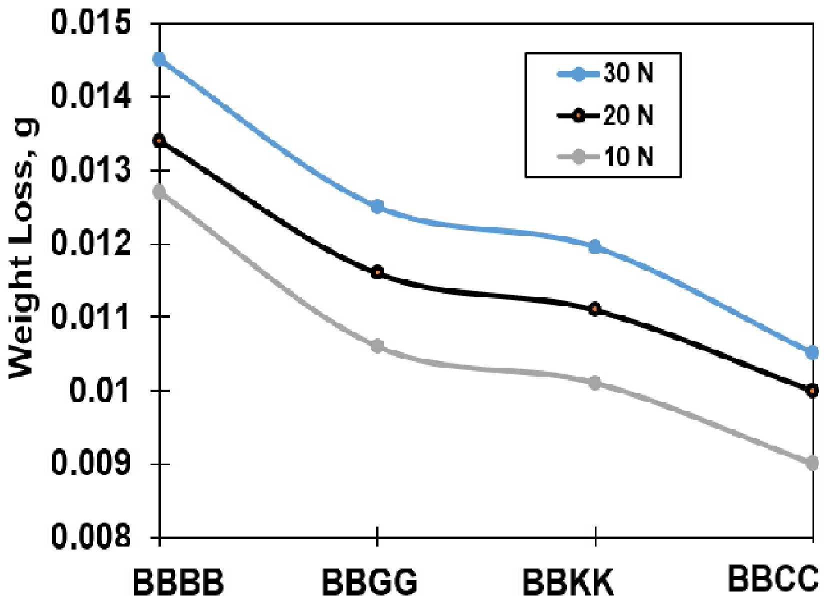

Figure 9: Loss of weight of the samples at 1.5 m/s for 10, 20, and 30 N.

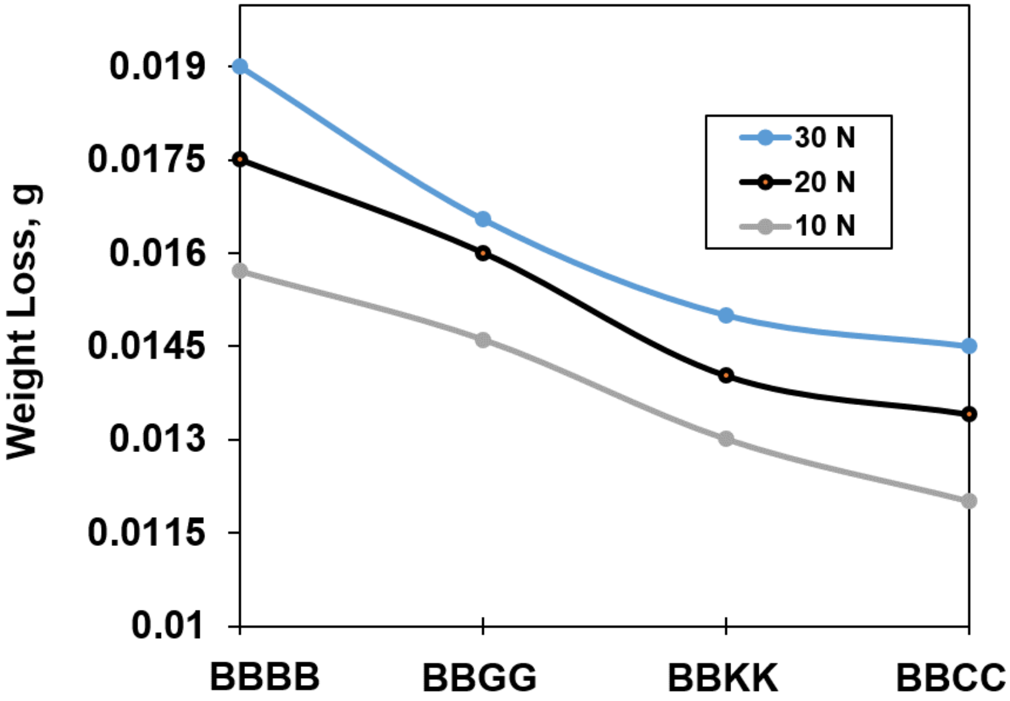

Figure 10: Loss of weight of the samples at 3.0 m/s for 10, 20, and 30 N.

4.3.3. Coefficient of Friction

The Coefficient of Friction (COF) data for composites comprising BPSF, Kevlar, carbon, and glass fibres for 1.5 and 3.0 m/s were presented in Figure 11 and Figure 12, respectively. The results demonstrate that the addition of synthetic reinforcements leads to a reduction in COF. The unhybridised composite (BBBB) exhibited the highest COF, followed by BBGG and BBKK, while the lowest COF was observed in BBCC. Interestingly, unlike the analysis of wear rate, the COF reached its minimum point under a 10N load. As the load increased to 20N and 30N, the COF also increased accordingly. Similarly, an increase in speed resulted in a proportional increase in the COF. It was observed that the incorporation of synthetic fibres through hybridisation had a diminishing effect on the COF of the composite samples.

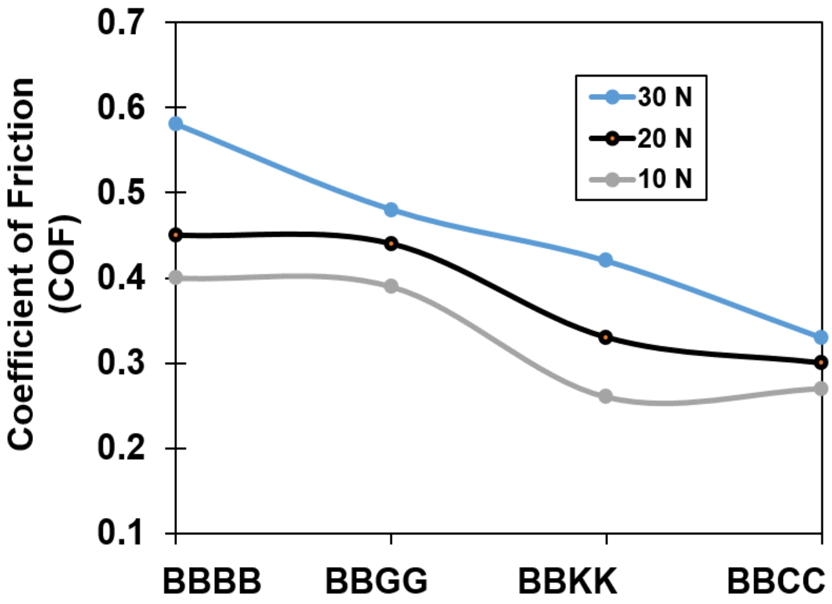

Figure 11: Coefficient of friction of the composite samples at 1.5 m/s for 10, 20, 30 N

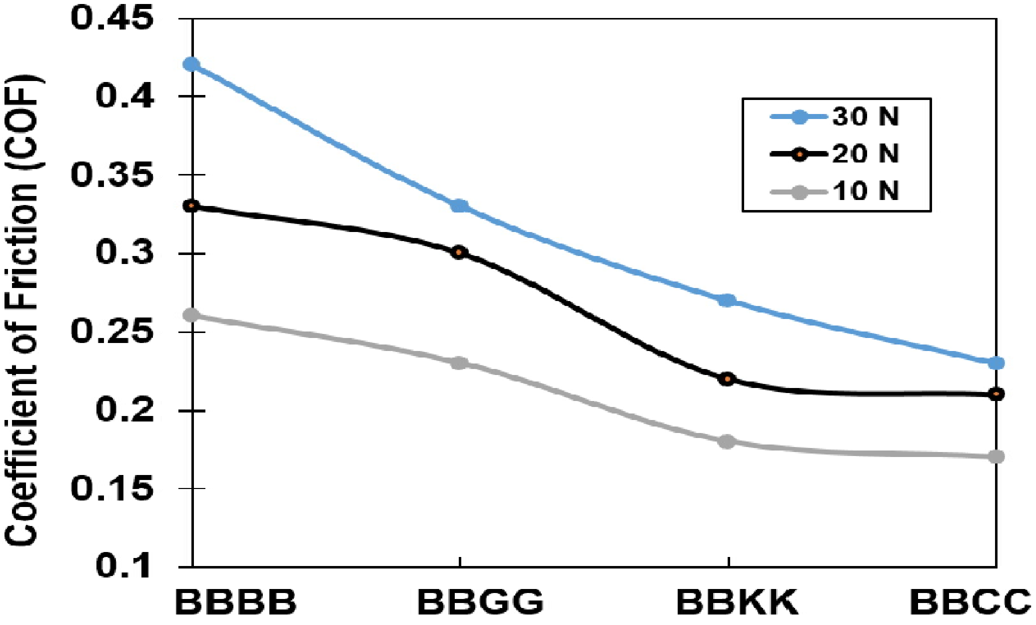

Figure 12: Coefficient of friction of the samples at 3.0 m/s for 10, 20, and 30 N

4.4. Microstructural analysis

The SEM analysis of the fractures from tensile strength tests for BBBB, BBCC, BBKK and BBGG are presented in Figure 13, Figure 14, Figure 15 and Figure 16, respectively. The microstructural micrograph captured the magnification for 400x, 1000x and 2000x for all composite samples. The BBCC, containing the hybrid of BPSF and carbon fibre, revealed a smooth surface and evidence of excellent bonding and homogenous fibre/matrix interaction as a result of little voids but noticeable dimples in its structure (Figure 14).Like the Figure 13, BBKK (Figure 15) displayed a better fibre/matrix dispersion. With BBGG, defects of void and fibre pullout were noticed (Figure 16). However, the unhybridised BBBB (Figure 13) samples revealed the presence of pores on its surface, thereby diminishing the tensile strength and ductility. There were evidence of agglomeration noticeable in mixture as well as debonding due to presence of hydrophilic sites in the cellulose sites. Also, the impregnable lignin cementing action and lack of chemical reaction to remove the hemicellulose might have contributed to the visible debonding and fibre pull out. Consequently, this makes the composite to be brittle and induces cracking since moving form elastic realm to plastic region is an indication of fracture. The cracks, void and other defects that protruded along composite surface are also visible and can be interpreted to be the presence of ductility and brittleness. Surface and tightening pressure may be responsible for the protruding defects along the sample surface. It can also be recalled from the earlier sections in this study that the mechanical and thermal stability of BBCC and other hybrid samples (BBGG and BBKK) are well above the unhybridised BBBB. Similarly, wear rate was also minimal with BBCC. This above assertion clearly justified the homogeneity and well dispersed fibre in the epoxy matrix as observed in BBCC. Other studies elsewhere also reported improved bonding with addition of synthetic reinforcement with a natural fibre composites(Hossain *et al.*, 2020; Kumar & Irfan, 2021; Sharma *et al.*, 2021).

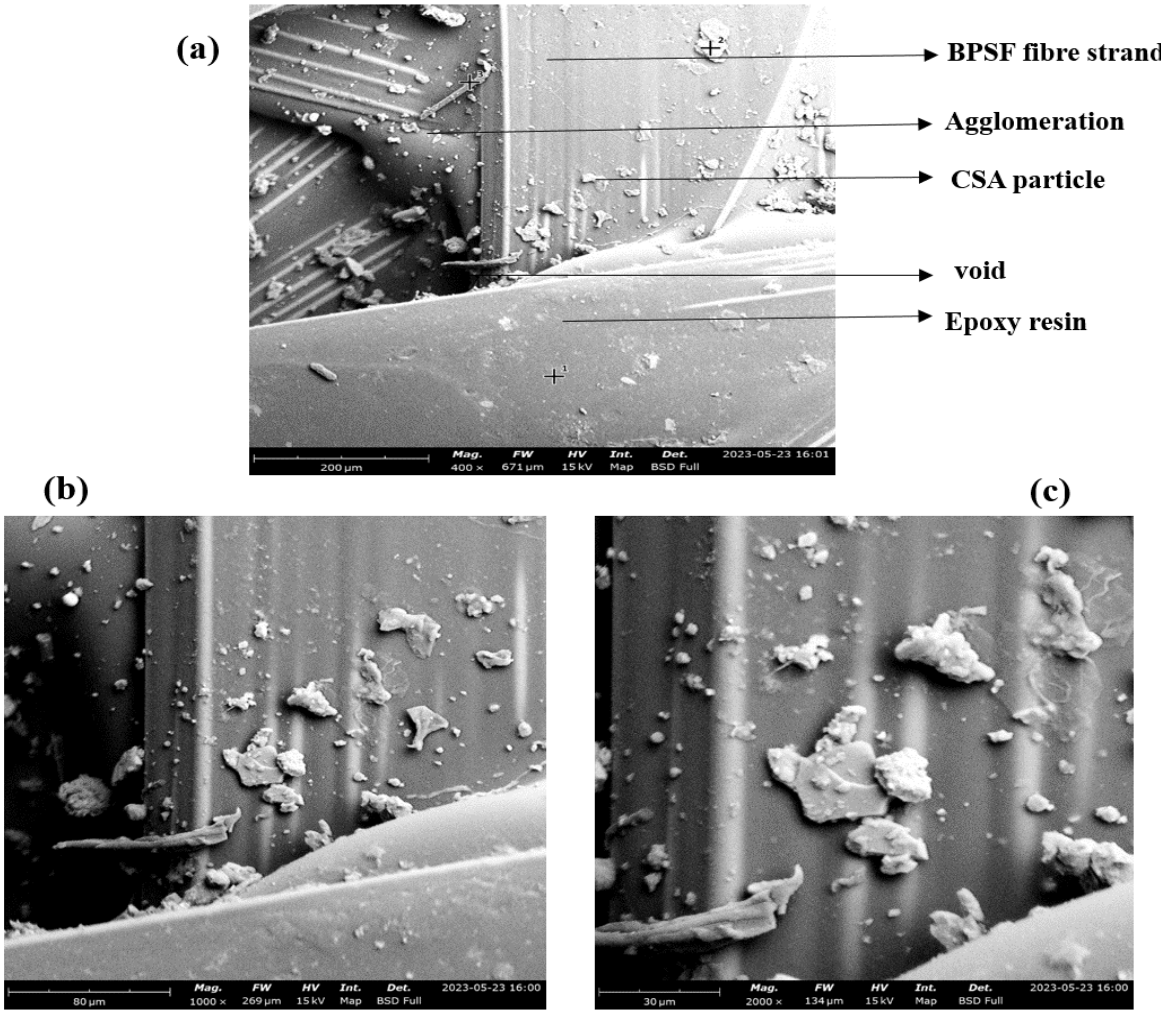

Figure 13: SEM of BBBB sample (a) 400x (b) 1000x (c) 2000x magnifications.

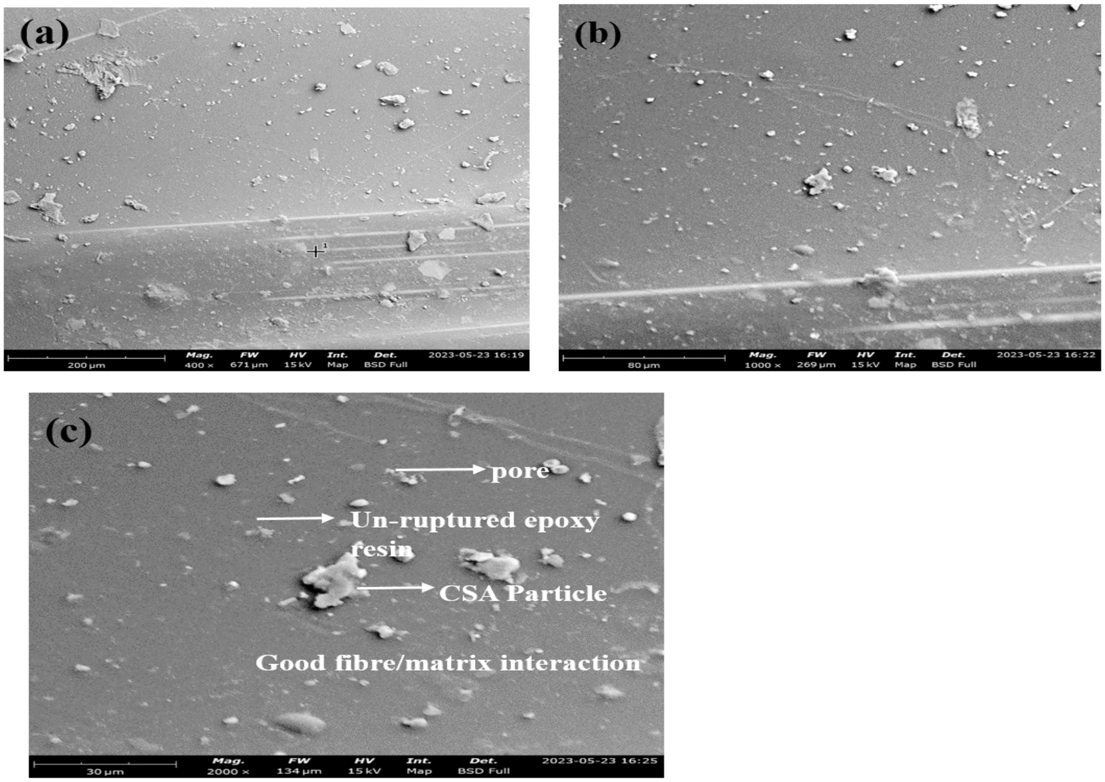

Figure 14: SEM of BBCC sample (a) 400x (b) 1000x (c) 2000x magnifications

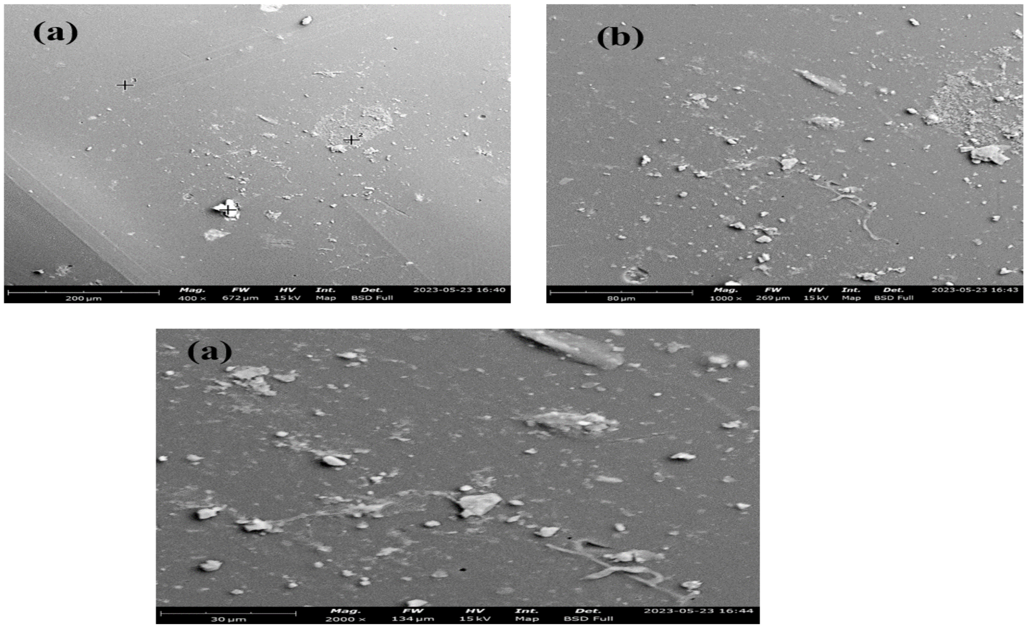

Figure 15: SEM of BBKK sample (a) 400x (b) 1000x (c) 2000x magnifications.

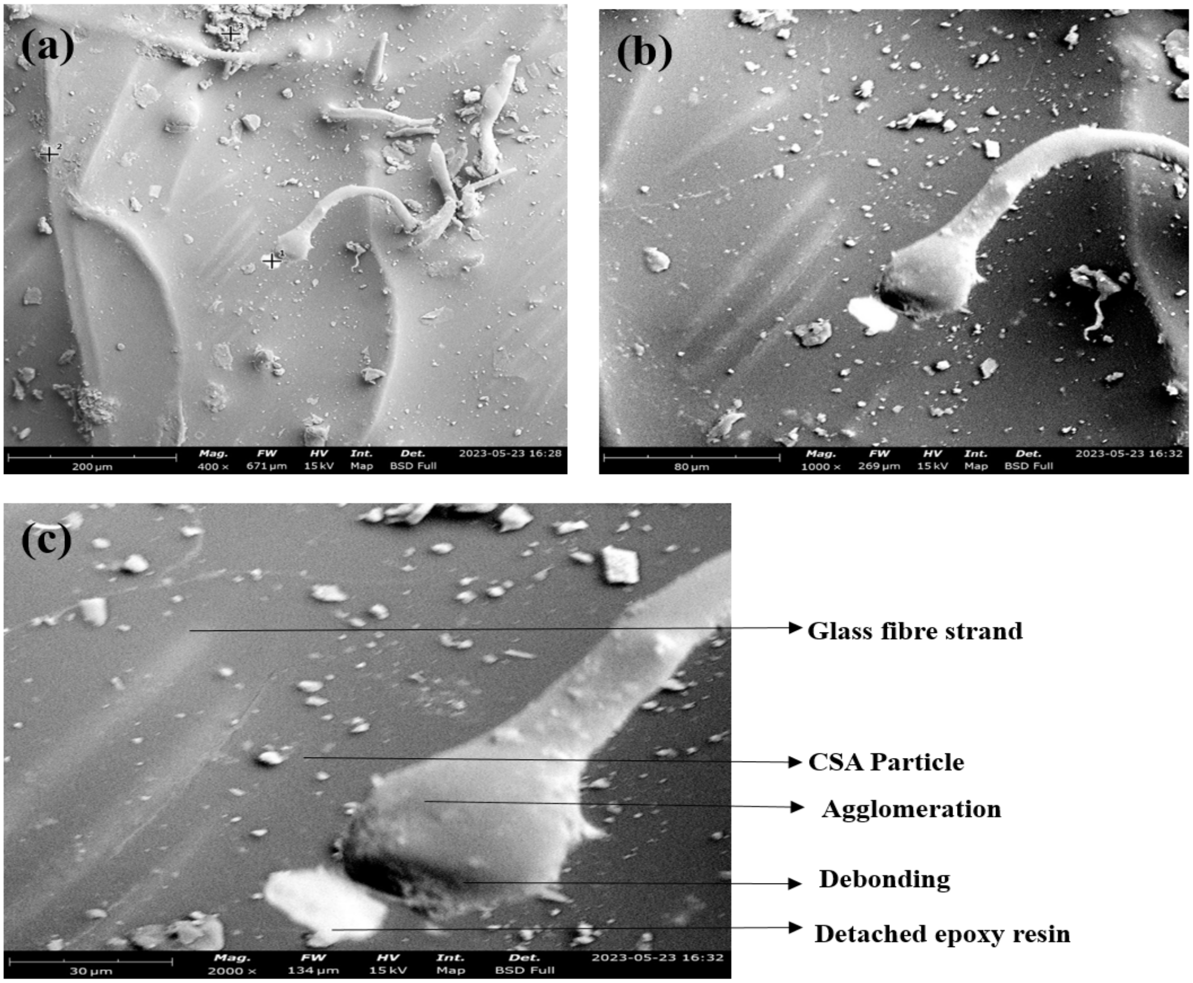

Figure 16: SEM of BBGG sample (a) 400x (b) 1000x (c) 2000x magnifications

5. Conclusion

In this work, attempt was made to examine the synergistic influence of incorporatingbanana pseudo stem fibre and synthetic fibre as reinforcements into epoxy-based hybrid composites. Banana pseudo stem fibre was reinforced with epoxy resin, and then hybridised with synthetic fibres (Carbon, Kevlar, and Glass) to develop four epoxy-based composites. One unhybridised composite (BBBB) containing only banana pseudo stem fibre as reinforcement. The remaining three are hybridised epoxy-based composites reinforced withbanana pseudo stem fibre and synthetic fibre to produce BBKK, BBGG, and BBCC. The 2 wt. % of coconut shell ash in the composites servedas aiding agent for enhanced hardness. The synthetic fibres successfully prevented the inherent hydrophilicity and occupied the cellulosic sites present in the composites. Therefore, the addition of synthetic fibres led to improvements in thermal resistance, compressive strength, tensile strength, and hardness properties of the hybridised epoxy-based composites. The SEM analysis of the resin and reinforcement interactions in the samples demonstrated that the hybridised samples exhibited a homogeneous structure. Compared to the unhybridised BBBB sample, the synergistic use of banana pseudo stem fibre and synthetic fibre enhanced the tensile and compressive strengths of the hybridised composite samples. In contrast to the unhybridised BBBB sample, the hybrid samples exhibited higher mass residue at elevated temperatures, with the BBCC sample demonstrating superior thermal stability at 18%. Furthermore, the hybridised samples exhibited lower wear rates and weight loss compared to the BBBB sample. Additionally, increasing the load and sliding speed resulted in substantial increase in wear rate, coefficient of friction (COF), and weight loss. Hybridised composites showed notable improvements in friction coefficients, wear rates, and weight loss compared to the unhybridised samples.The epoxy-based hybrid composites reinforced with banana pseudo stem fibre and synthetic fibre (Carbon, Kevlar, and Glass) exhibited better properties when compared to the unhybridised composite sample. Sample BBCC, epoxy-based hybrid composite reinforced with banana pseudo stem fibre and carbon fibre exhibited the best mechanical, thermal stability, tribological and microstructural characteristics.

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