Chapter 6
Two-Body Abrasion of Bamboo Fibre/Epoxy Composites

A. Oun and B.F. Yousif

Abstract In this chapter, a new polymeric composite was developed. Bamboo fibre reinforced epoxy (BFRE) was build using unidirectional configuration and hand lay-up techniques. The bamboo fibres were treated with 6 % NaOH to improve their interfacial adhesion as recommended by the literature. The tribological performance of the new composites was investigated in terms of two-body abrasion considering different sliding distances and applied loads. Normal orientation of the fibre onto the counterface is considered in this study. For comparison purposes, neat epoxy and epoxy composites based on glass fibres were tested as well under the same conditions. Different grades of SiC papers were used in this study and optical microscopy assisted to observe the abrasive papers and the worn surfaces of the samples after the tests. The results revealed that the wear rate of the BFRE composites is very competitive to the glass fibre/epoxy composites and the neat epoxy as well at all the grades of the SiC papers. The grade of SiC papers significantly influenced the wear and frictional behaviour of the composites since the low grade exhibited higher wear rate and high friction coefficient due to the intimate contact of the asperities (interlocking process during the rubbing). Optical microscopy and SEM micrographs showed different damage features on the worn surfaces such as ploughing, grooving, scratching which represented the abrasive wear. SiC papers were either covered by patches of the soft part (epoxy or its composites) or contained loss debris from the soft parts.

1 Introduction

Nowadays, the increased demand for the use of environmentally friendly composite materials based on natural fibres is an attractive idea to many researchers in the area of tribology. This is basically due to the advantages of these fibres compared to

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synthetic fibres which are low cost, non-abrasive, recyclable, and possess good mechanical properties. Therefore, many studies focus on the opportunity of using natural fibres in the reinforcement of polymer composites instead of inorganic fibres. Bamboo fibre is considered to be one of these natural fibres, having a small diameter, and strong interfacial adhesion to resin matrix. Recently, many investigations have been conducted on the tribological properties of polymer composites reinforced with natural fibres such as kenaf, coir, oil palm, and jute fibres. The outcomes of these works have revealed a very high coefficient of friction in the polymer composites and low wear performance because of poor interfacial bonding between those fibres and the polyester which leads to a removal of the high layer of composite surface. On the other hand, the frictional and wear characteristics of the fibres reinforced epoxy composites were controlled using chemical treatments like alkali treatment in order to improve the interfacial bonding among the fibres and the matrix. For example, Chand and Dwivedi [1] have reported improving abrasive wear resistance of the treated jute fibres with the epoxy matrix compared to untreated fibres. With regards to the reinforcement of polymer composites by using natural fibres as filler for tribological application, few works have been carried out to investigate the tribological performance of natural fibres in abrasive and adhesive wear modes [11, 2]. The current research examines the adhesive wear and two-body abrasion of bamboo fibre/polyester composites. Three materials were selected for this research and were tested under different dry contact conditions (applied load and sliding distance) using different abrasive paper grades. The literature reveals studies into the tribology behaviour of polyester composites reinforced with natural fibres like betel nut [18], kenaf, coir, sugarcane [7], jute [1]. Although these studies presented various surface damage features which resulted from tests at different sliding conditions, not one of them focused on the adhesive wear and two-body abrasion of the polyester composites. The main aim of this project is to develop a new biocomposite and test its tribological performance.

2 Material Preparation and Experimental Procedure

2.1 Material Preparation

The materials used in this project were the same as materials that have been used in the previous studies by many researchers such as [8, 11, 12]. They are bamboo fibre reinforced epoxy (BFRE), glass fibre reinforced epoxy (GFRE), and neat epoxy (NE). The objective of the use of these materials is to show the characteristics of surface damage when tests are conducted under different dry loading conditions. So the possibility of attempt with new materials may not clearly show surface damage as in these materials. The experiments were conducted in three different abrasive paper grades which are G1200, G400, and G80.

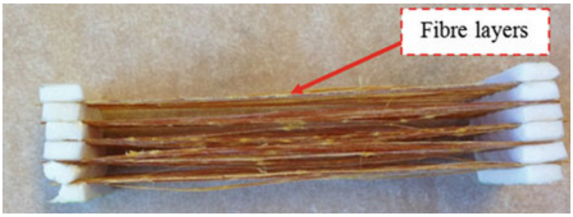
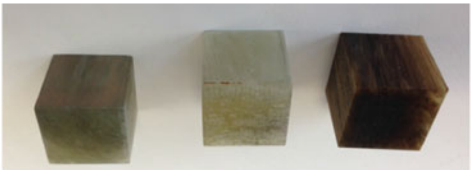


Fig. 1 Picture of prepared bamboo fibre structure

Raw bamboo fibres were provided from the Malaysian Agricultural Research and Development Institute (MARDI). The fibres were sorted in equal diameters and then the process of combing these fibres was conducted before placing them into a plastic mould with 6 % of NaOH solution. The fibres were left immersed in chemical treatment for 24 h at a room temperature of 27 °C. After the treating process, the fibre surface was thoroughly cleaned of impurities and increased roughness of fibre surface was clearly observed. This was due to the alkaline treatment which leads to the possibility of enhancing the interfacial bond strength between the fibre and the epoxy matrix as reported by Yousif and El-Tayeb [17]. Also, according to Nirmal et al. [10], the chemical treatment helps to enhance the wear performance and reduces the porosity of a composite. In the next step, the bamboo fibres were cut into a uniform length of 170 mm and placed in a unidirectional format. Before being placed into a metal mould, the end of fibre sides were pasted together with double-sided tape to make the first layer of fibre structure. This step was repeated until the completion of the composite structure as shown in Fig. 1.

2.2 *Preparation of Composites*

The fabrication process of the composite has begun by coating the inner walls of the metal mould with a light layer of wax which works to prevent sticking between the mixture and the mould allowing easy removal after the curing process. Treated bamboo fibres were organized and placed into a metal mould, with dimensions 70 mm × 10 mm × 10 mm, in a unidirectional form. In this work, a liquid of epoxy resin (DER331) is used. The ratio of epoxy resin to hardener in this study is 2:1. The mixture was uniformly mixed as a result of using an electric stir and was then poured into the metal mould. To avoid generating air bubbles, the mixture sat between 5 to 10 min before being pouring into the metal mould. The mould remained at a vacuum room (MCP004PLC) at 27 °C to cure for 24 h. After that the mixture was treated in an oven for another 24 h at 80 °C with 10 kPa pressure. Fibre volume fraction in the matrix was around 48 % Vol. Bamboo fibre reinforced epoxy (BFRE), glass fibre reinforced epoxy, and neat epoxies were selected as reinforcement materials in this research. More information about material preparation has been given by Chin and Yousif [5]. The composite block was machined into



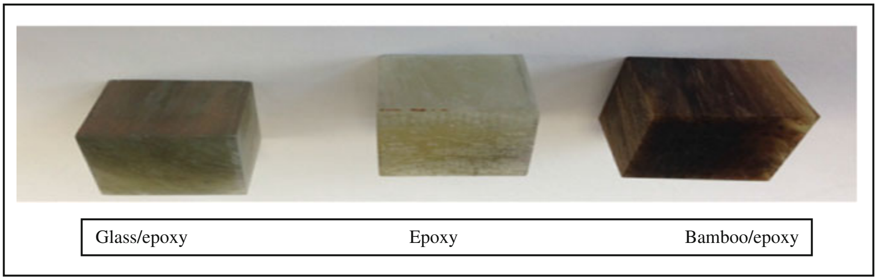


Fig. 2 Sample of the prepared composites

specimens of 20 mm × 10 mm × 10 mm and the tribological tests were conducted in 20 mm × 10 mm. In the fabrication process of synthetic composite, a similar method was used for mixing the epoxy liquid with hardener in the ratio of 2:1 and glass fibre replaced the bamboo fibre. The photo of the composites is presented in Fig. 2.

The sliding conditions were selected in this study depending on previous studies which have been performed to investigate tribological and mechanical behaviours of fibre polymer based on natural fibres. Of these sliding parameters for dry contact conditions, there were sliding distances (1.35–20.25 m), a sliding speed of 2.8 m/s, and changeable applied loads between 25 to 100 N. During the dry contact condition test, changeable applied loads were among 25–100 N for bamboo fibre reinforced polyester (BFRP), glass fibre reinforced polyester (GFRP), and neat epoxy (NE).

2.3 Experimental Procedure

A Block-On-Ring (BOR) machine was used to carry out the tests. This machine was adapted for wet and dry contact sliding tests. Figure 3 reveals the major components of the machine which are a stainless steel counterface, load position, load cell, specimen holder, and control panel. The load cell is used to measure frictional forces that are generated between the counterface and the specimens. During dry contact tests, the interface temperature was measured by using an infrared thermometer that was pointed in the mid-point of interface between the counterface and the specimen. With regards to the abrasive paper grade, it is fixed on the surface of the ring counterface as shown in Fig. 3.

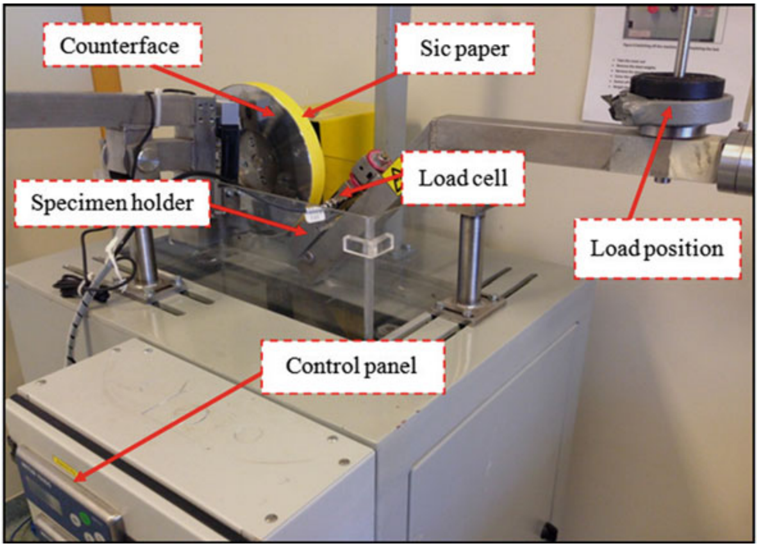


Fig. 3 Main parts of a Block-On-Ring (BOR)

Experiments were performed using a Block-On-Disk (BOD) machine. The composite surface specimens (20 mm × 10 mm × 10 mm) was tested against a firm counterface made of stainless steel (AISI 304, Ra = 0.1 μm, hardness = 1250 HD). All the specimens' contact surfaces were cleaned with a dry soft brush. The counterface surface was cleaned with a wet cloth and acetone, and then dried by a soft cloth and hot air at around 100 °C for 5 min before being fixed the abrasive paper grade.

To ensure more intimate contact between the counterface and abrasive paper, they were pasted by double-sided tape. Moreover, the specimen was fixed in the specimen holder to ensure that it did not remove during the test ensuring full contact with the counterface. The experiments were performed in changeable applied loads between 25 and 100 N, sliding speed of 2.8 m/s, and sliding distances (1.35–20.25 m) in room temperature of 27 °C. The dry soft brush was used to clean the prepared composite samples pre and post the test. Prior to and after the test, weights of all specimens were determined by using Setra weight balancer (±0.1 mg) and then weight loss was computed. Friction force was determined via load cell during the tests.

The SEM machine was used to study the composite surface morphology. The specimen surfaces were covered with a light layer of platinum before using the SEM machine. Before tabulating the average results, every tribological test was repeated three times. Many various surface observation methods can be used to show surface damage and to obtain the required results, including optical microscopy and Joel SEM machine.

3 Results and Discussion

3.1 Tribological Performance of Synthetic and Natural Fibre Reinforced Epoxy Composites Under Different Dry Contact Conditions

The experimental outcomes of the neat epoxy, glass, and BFRE composites are presented in this chapter under different operating parameters using different abrasive paper grades. Surface observations are introduced in the wear rate of the composite surface, and the coefficient of friction by using scanning electron microscopy and optical microscopy. The relationship between the wear rate, applied load, and sliding distance are plotted in the charts as well. To study wear and frictional performance for the polymer composite based on synthetic and natural fibres subjected to different sliding conditions, a set of tests was carried on the neat epoxy, bamboo/epoxy, and glass/epoxy materials in order to achieve this aim under different applied loads using different abrasive paper grades, with a sliding distance from 1.35 to 20.25 m. The results are represented on individual charts. The tribological outcomes of the polymeric composite reinforced with neat epoxy, glass epoxy composite, and bamboo epoxy composite are plotted in Figs. 4 to 14 with comparisons between them. The graphs illustrate the wear rate and the friction coefficient of the selected materials under different applied loads using different abrasive paper grades.

3.2 Wear Performance of Bamboo

Figure 4 displays the wear rate of the bamboo epoxy composite under different applied loads using different abrasive paper grades. Figure 4a demonstrates an increase in the wear rate values of the BFRE composite in the lower range of the applied load between 25 and 50 N. An increase in the applied load of more than 50 N has a significant impact on the values of the wear rate. In Fig. 4b, c shows similar findings compared to the previous figure when the applied load increases. The increase in the applied load showed reduction in the wear rate of bamboo epoxy composite and this is mainly due to the end of the fibres helping to carry the load out of the polyester region and resisting the shear strength. Further discussion is given in the scanning electron microscopy section.

There is a decrease in the wear rate values of bamboo fibre reinforced epoxy composite when the applied load increases and this result is presented in Fig. 4a–c. All of these charts show the steady state of the wear rate of the BFRE after around 15 m sliding distance, but there is a very high wear rate recorded before this sliding distance. It can be observed that all figures display an increase in the wear rate value

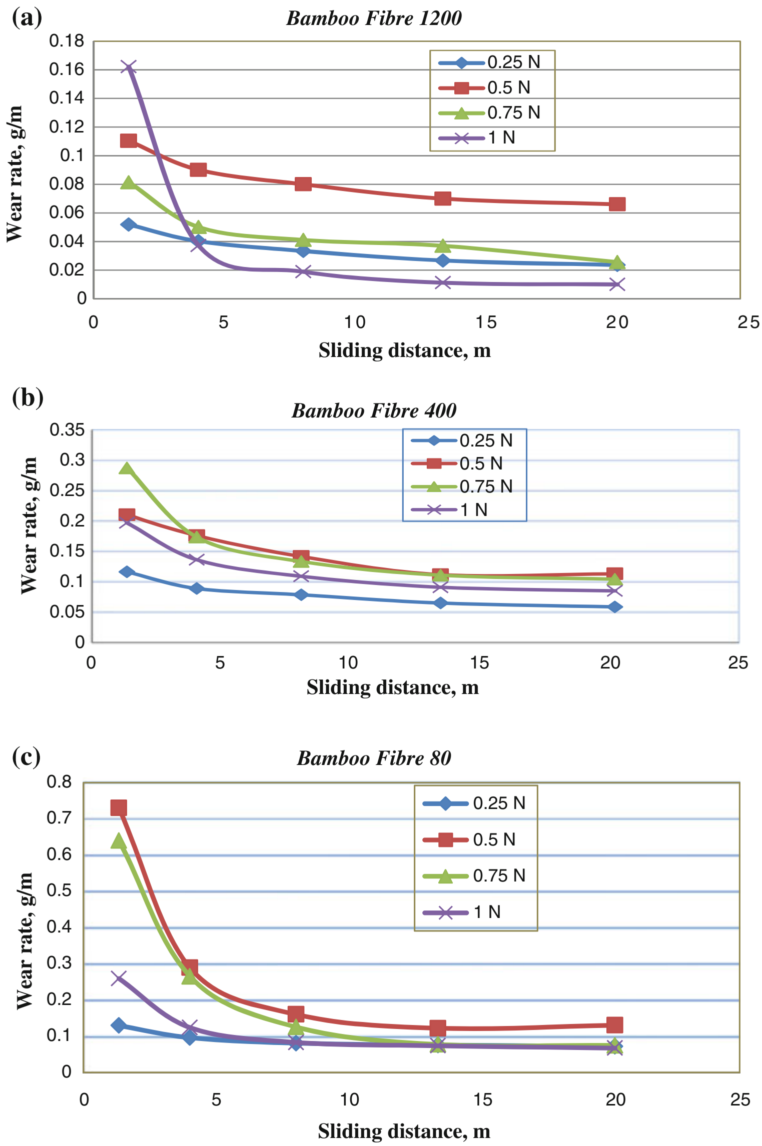


Fig. 4 Wear rate of bamboo fibre reinforced epoxy composite under different applied loads using different abrasive paper grades

of the bamboo epoxy composite in the lower range of the applied load between 25 and 50 N. The highest wear rate value is recorded at applied load (50 N), while the lowest value of wear rate is recorded with an increasing load applied to 75 N and then to 1 N compared to the previous value of the applied load (50 N). This means that there is the possibility of replacing the glass fibre with bamboo fibre due to decreased wear rate. The major reason for the decrease in wear rate is the high interfacial adhesion of bamboo fibres to the synthetic matrix. This has been investigated by some recent researchers such as [4, 14]. Generally speaking, all tested parameters (such as applied load and sliding distance) have an effect on the wear outcomes.

3.2.1 Neat Epoxy Wear Rate

Figure 5 shows the wear rate of the neat epoxy under different applied loads using different abrasive paper grades. Figure 5a shows that the increase in the sliding distance decreases the wear rate for all the applied loads. For the applied load, there is no clear trend can be drawn. Figure 5b shows similar results as in the previous Fig. 4a when the neat epoxy is subjected to the increase in applied load, however, at the grade of 80 Fig. 5c shows that the increased applied load increases the wear rate.

The increase in the sliding distance showed a decrease in the wear rate and this could be due to the filling of the abrasive paper while the rubbing process continues. In other words, a steady state is reached after about 15 m. This will be further explained with the aid of the optical microscopy in the next sections. From the findings shown in Fig. 5, it can be seen that a high degree of outcome fluctuation at the outcomes could be observed at all applied loads. This fluctuation phenomenon is due to the clean surface of abrasive paper in the beginning run period when the wear is initiated in epoxy region [17, 14, 19]. Wear rates begin a gradual decline with increasing sliding distance until a steady state condition is reached.

3.2.2 Wear Performance of Glass

Figure 6 presents the wear rate of the glass epoxy composite under different applied loads using different abrasive paper grades. Figure 6 demonstrates an increase in the wear rate values of GFRE in response to the increase in sliding distance. In Fig. 6b, a similar trend of an increasing wear rate value was observed with an increase in sliding distance for all applied loads, however, in the grade of 400 Fig. 6c displays that the wear rate curve has no clear trend at a sliding distance between 1.35 and 20.25 m for all applied loads. In general, the increase in the sliding distance showed increase in the wear rate and this is due to the brittleness of glass fibres. This will be further clarified in the surface observation section.

From the test results obtained, the charts explain that after a 15 m sliding distance (steady state condition), the value of the wear rate of the glass epoxy

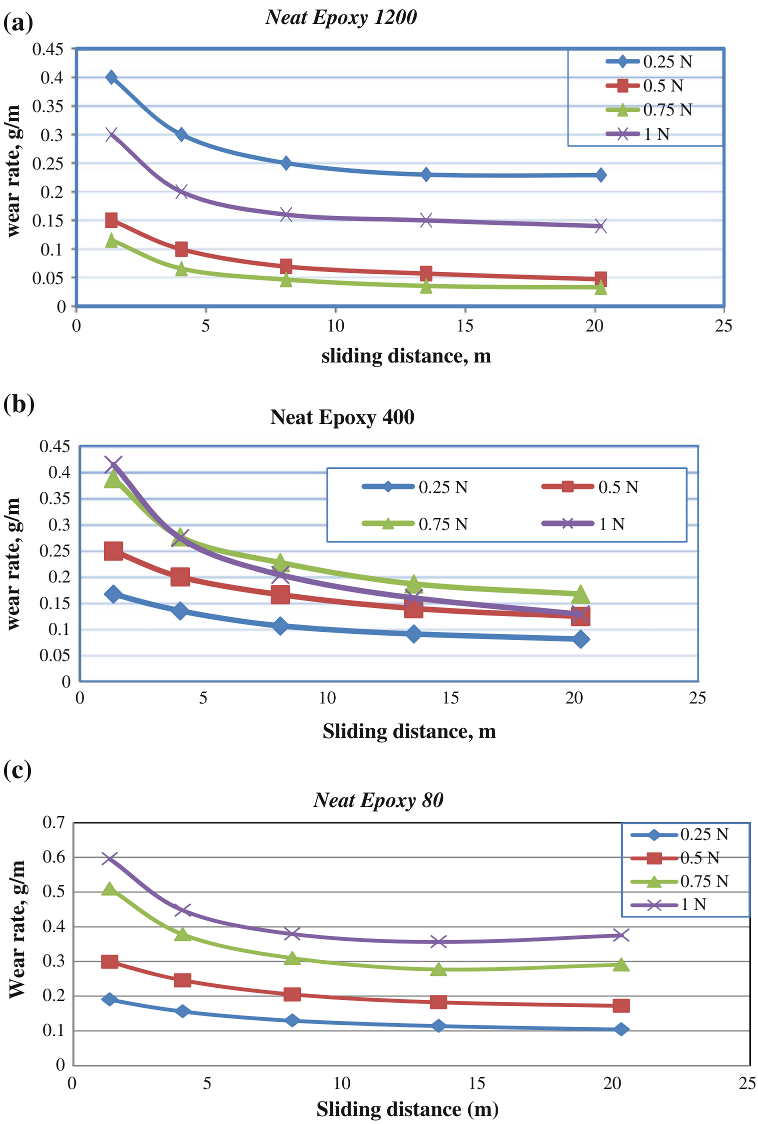


Fig. 5 Wear rate of neat epoxy under different applied loads using different abrasive paper grades

composite increased and was in the range of 0.1–0.4 g/m for all applied loads. The average of wear rate was initially between 0.1 and 0.2 g/m for a sliding distance between 1.35 and 20.25 m. However, the wear rate increased when the applied load increased. Also, a similar trend in increasing wear rate was observed with other

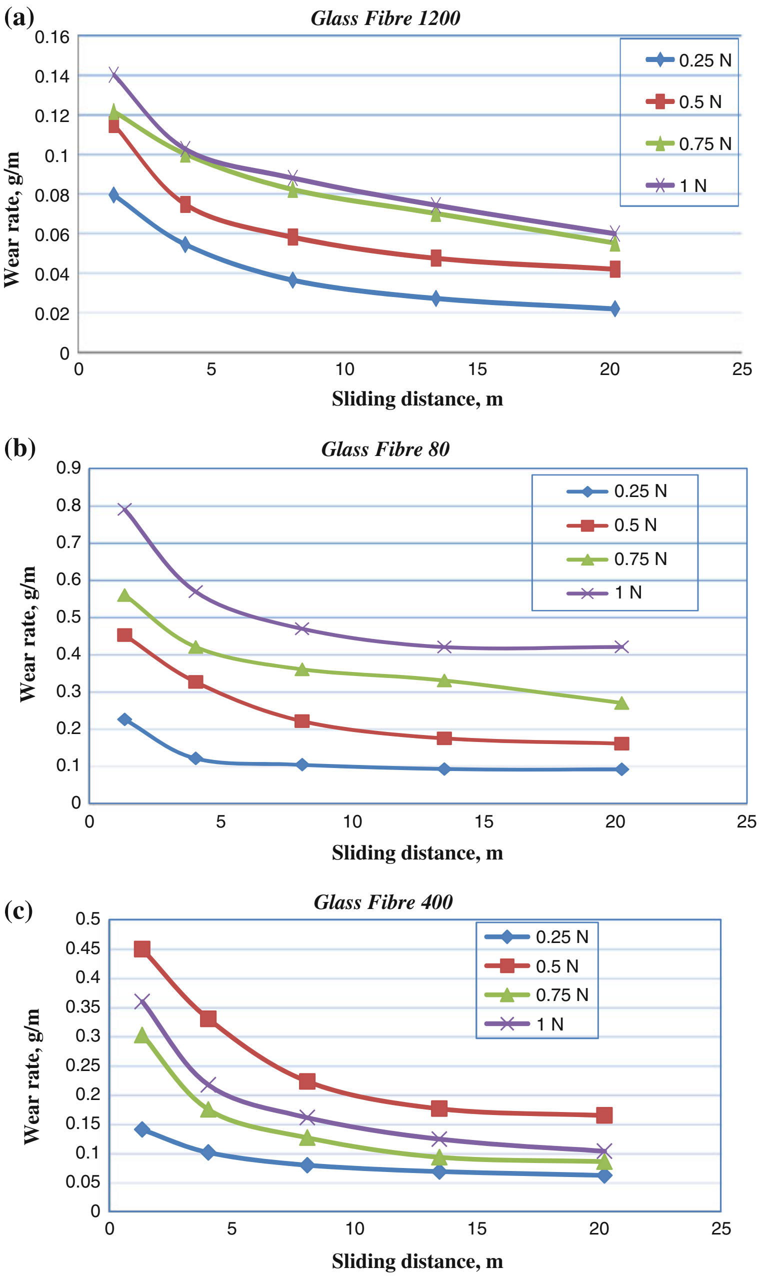


Fig. 6 Wear rate of glass fibre reinforced epoxy composite under different applied loads using different abrasive paper grades

synthetic fibre reinforced polyester composites. Many works have reported this phenomenon, such as [10, 17]. Overall, the curve of the wear rate of the glass epoxy composite has an increasing trend in all applied loads with respect to sliding distance and this suggests another potential for replacing the synthetic fibre with bamboo fibre.

3.2.3 Comparison of Wear Performance of Neat Epoxy and Its Composites

The comparison between the wear performances of the BFRE composite, the GFRE composite and neat epoxy (NE) under an applied load of 1 N using different abrasive paper grades (presented in Fig. 7a–c) shows the remarkable influence of operating parameters on the wear outcomes. All graphs clearly display that at a sliding distance of 20 m, the wear rates of the BFRE composite for all grades have lower values compared to others. This indicates that the wear rate values of the bamboo epoxy composite for all applied loads decrease when the sliding distance increases. At the higher applied load of 1 N, the high values of the wear rate in the neat epoxy followed the GFRE composite at all grades except for the grade of 80, the maximum value of the wear rate in the GFRE composite followed the neat epoxy. Steady state conditions for all materials were reached after about 15 m sliding distance. From the above outcomes, the bamboo epoxy composite demonstrates higher wear resistance in all applied loads compared to other fibres and this is due to stronger interfacial adhesion of bamboo fibres with the epoxy matrix, which prevents the bending and pulls out of the fibres at the rubbing area. At sliding distance of 20 m, the average results for the wear rate of BFRE were between 0.02 and 0.12 g/m, while for the glass epoxy composite results were in the range of 0.06–0.4 g/m, and the neat epoxy was between 0.14 and 0.39 g/m at applied load of 1 N. In other words, there is a remarkable difference in the wear rate for the neat epoxy and its composites under the same applied load and siding distance of 20 m. From the figures below, it can be noted that the presence of bamboo fibres in the polyester matrix improved the wear behaviour of the neat epoxy. Furthermore, the graphs indicate that the composite based on natural fibre possesses better wear behaviour than the synthetic fibre. In other words, bamboo fibres help in the reduction of the wear rate of the epoxy particularly when the applied load increases. This means that for adhesive wear applications there is the potential of using bamboo fibre to reinforce polyester composites and replacing glass fibres. This is due to the promising results of bamboo fibres which have a high interfacial adhesion between the fibre and the epoxy matrix. This has been reported by many researchers like [10, 17].

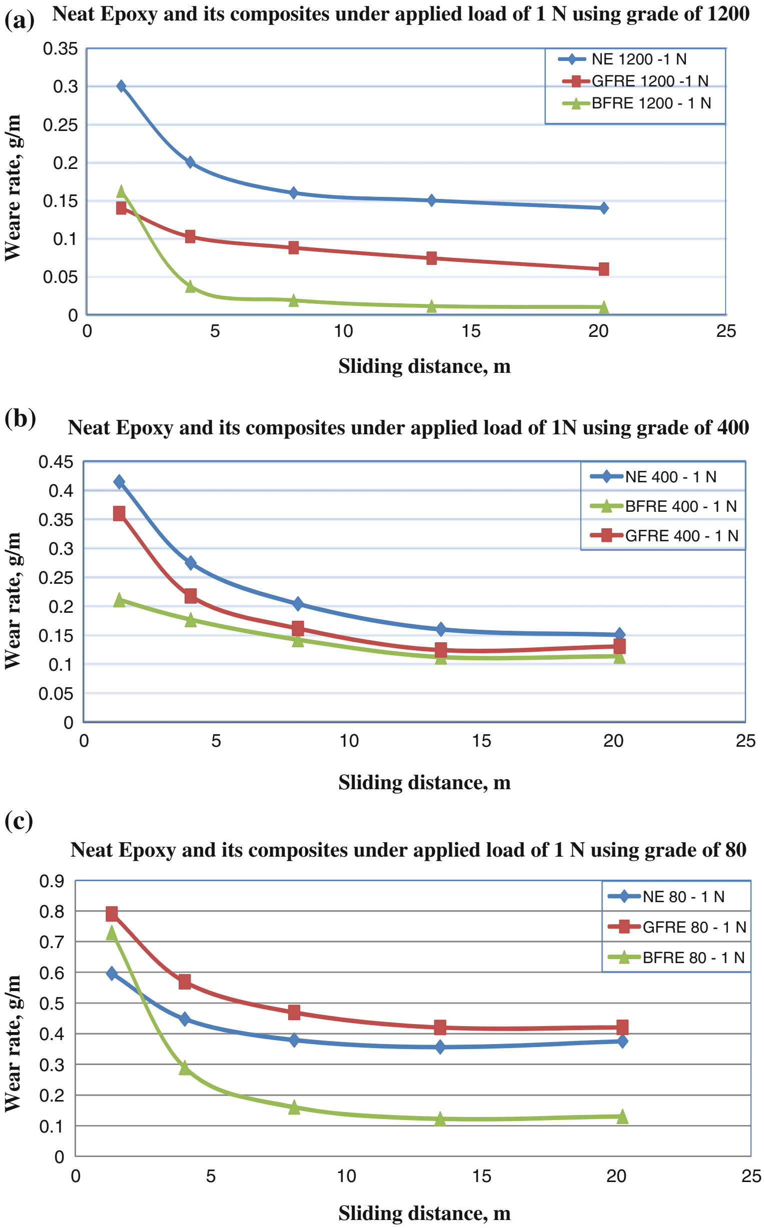


Fig. 7 Wear performances for neat epoxy and its composites under applied load of 1 N using different abrasive paper grades

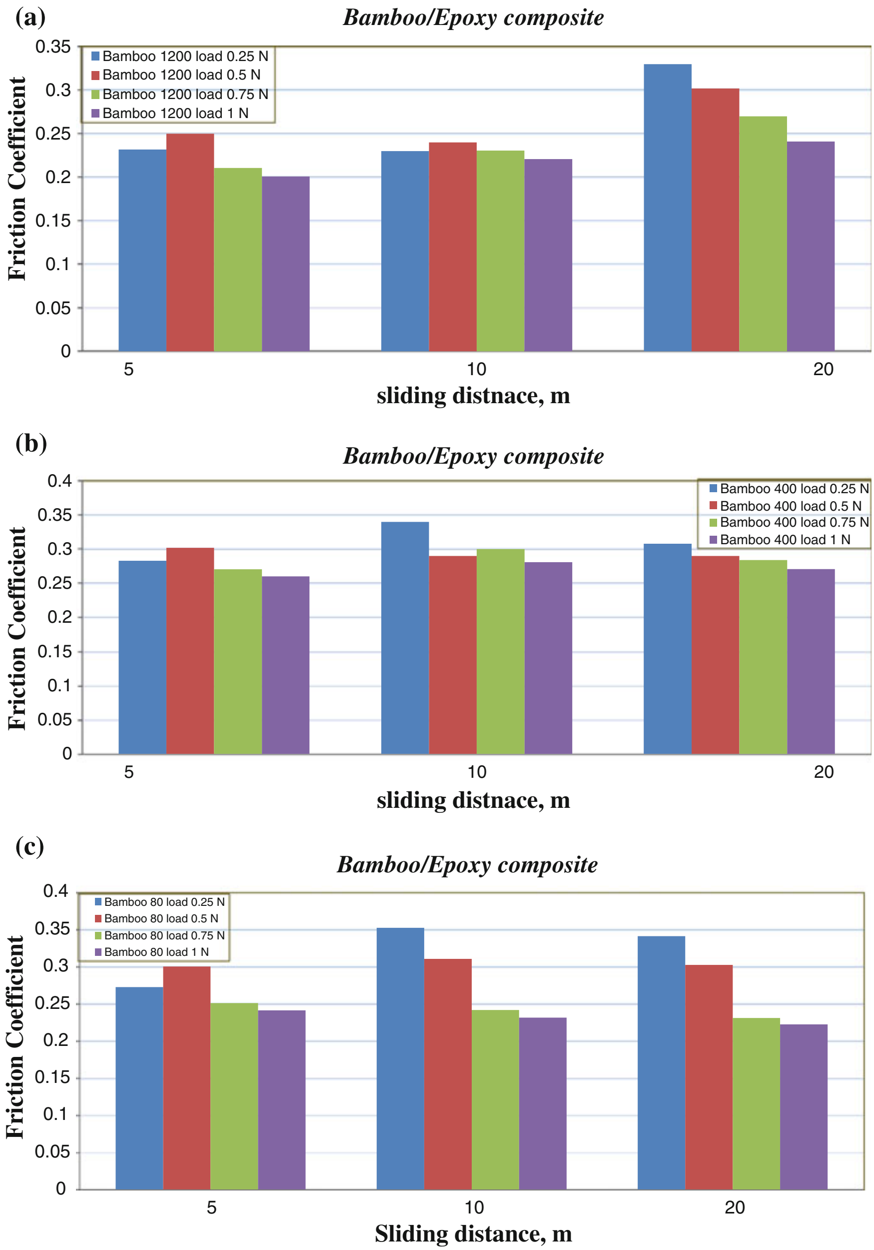


Fig. 8 Frictional performance of bamboo fibre reinforced epoxy composite under different applied loads using different abrasive paper grades

3.2.4 Frictional Performance of Bamboo

Figure 8 displays the friction coefficient values of the bamboo epoxy composite under different applied loads using different abrasive paper grades. In the case of grade 1200, Fig. 8a shows that, at sliding distance of 5–10 m, the friction coefficient values are scattered and the frictional curve for both sliding distances is similar in terms of up and down values at all applied loads. However, at sliding distance of 20 m, the friction coefficient decreases when the applied load increases. For the applied load, the curve for the friction coefficient declines when sliding distance increases.

At the grade of 400, Fig. 8b shows that the values of the friction coefficient for all sliding distances are also scattered, except for sliding distance of 20 m which indicates a decrease in the friction coefficient when the applied load increases. In Fig. 8c, no clear trend for the friction coefficient can be drawn before 10 m sliding distance but, after this sliding distance, a decrease in the friction coefficient occurs when the applied load increases. The range results of the friction coefficient for the grade of 80 are between 0.23 and 0.35 where the highest value of friction coefficient was measured at 25 N applied load at sliding distance of 10 m.

The average of the coefficient of friction for all applied loads was within 0.2 and 0.35. In general, the values of the friction coefficient were slightly increased and this is due to the fibres being exposed to the sliding surface. In other words, fibre ends contribute to protect the matrix region, which leads towards the increase in the friction coefficient. The highest value of the friction coefficient was measured at applied load of 25 N at the beginning of the period which was about 0.35. While the lower value of friction coefficient can be observed at a higher applied load of 1 N which was 0.2. At higher applied loads of 75 and 1 N, the BFRE composite shows lower values of friction coefficient for all graphs and this may contribute to the improved mechanical properties of polymeric composites. Moreover, it can be observed from the graphs that the coefficient of friction did not reach a steady state condition for all applied loads. In other words, there is no clear frictional trend for all graphs at all sliding distances in the BFRE composite due to the surface adjustment by treatment which enhances the interfacial adhesion between the fibre and the polyester matrix. This indicates that the bamboo fibre epoxy composite has a good wear resistance. Many investigations have been reported this like [6, 16].

3.2.5 Frictional Performance of Glass

Figure 9 exhibits the friction coefficient values of the glass epoxy composite under different applied loads using different abrasive paper grades. At grade of 1200, Fig. 9a shows that for all sliding distance increase the friction coefficient in the beginning run period and starts to be reached steady state of the friction coefficient

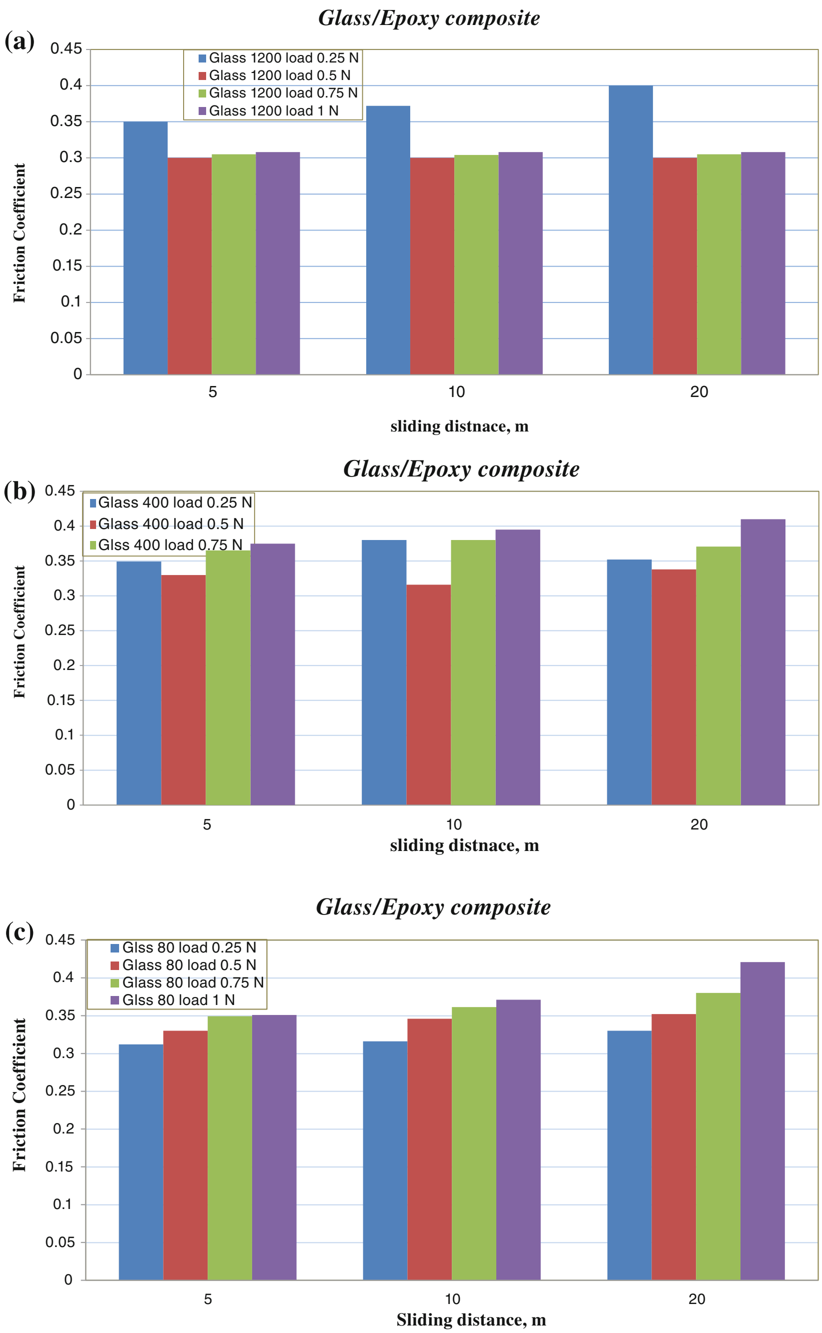


Fig. 9 Frictional performance of glass fibre reinforced epoxy composite under different applied loads using different abrasive paper grade

at different applied loads. The coefficients of friction for all applied loads are within the range of 0.29–0.31 except for the applied load of 25 N which was 0.4 at sliding distance of 20 m. Figure 9b shows the increase in the coefficient of friction more than 0.4 with the grade of 400. Moreover, it seems that the trend of the friction coefficient is not clear at all sliding distances. For the grade of 80, Fig. 9c shows that, for all sliding distances, the increase in the applied load increases the friction coefficient.

At different applied loads, the glass fibre demonstrates a friction coefficient above 0.25–0.42. In general, the values of friction coefficient of glass are higher compared to the bamboo. The lower friction coefficient of glass fibre can be achieved with the grade of 1200 at applied load of 50 N and sliding distance of 10, while the high friction coefficient of the composite can be observed in the grade of 80 with the applied load of 1 followed by the grade of 400. For all grades, there is an impact of sliding distance on the frictional behaviour of the composite at higher applied loads, especially at the grade of 80 where the increase in the applied load has a significant influence on the values of the friction coefficient. Each curve displayed a different trend in frictional forces as a function of sliding distance.

3.2.6 Frictional Performance of Neat Epoxy

Figure 10 shows the friction coefficient values of the neat epoxy composite under different applied loads using different abrasive paper grades. Figure 10a shows that the neat epoxy for all sliding distances demonstrates higher values of friction coefficient at an applied load of 25 N. The average outcomes for friction coefficient of the neat epoxy are between 0.31 and 0.42 at the grade of 1200 at all applied loads. At grade of 400, Fig. 10b shows that the increase in the applied load increases the coefficient of friction at a 5 m sliding distance, while for other sliding distances the values of the coefficient of friction are scattered due to the high contact pressure resulting from the various applied loads on the neat epoxy, which can cause limited bonding between hardener and epoxy resin. As a result of this, the inability of the neat epoxy to resist lengthy exposure for sliding distances can lead to micro- and macro cracks on the neat epoxy surface. In this chart, the highest friction value was measured at the high applied load of 1 N which is 0.39 at a sliding distance of 5 m, while the lowest value was 0.3 at a sliding distance of 10 m. For the grade of 80, Fig. 10c shows a similar trend in the friction coefficient to the previous chart Fig. 10b. In other words, the neat epoxy with the grade of 80 confirms similar friction performance to that of the grade of 400. This means that the applied load does not influence frictional performance of neat epoxy using different abrasive paper grades. Generally, the friction coefficient values are high, and are considered to be one of many issues that the adhesive wear performance of neat polyesters has. This has been reported by many authors like Suresha et al. [15]

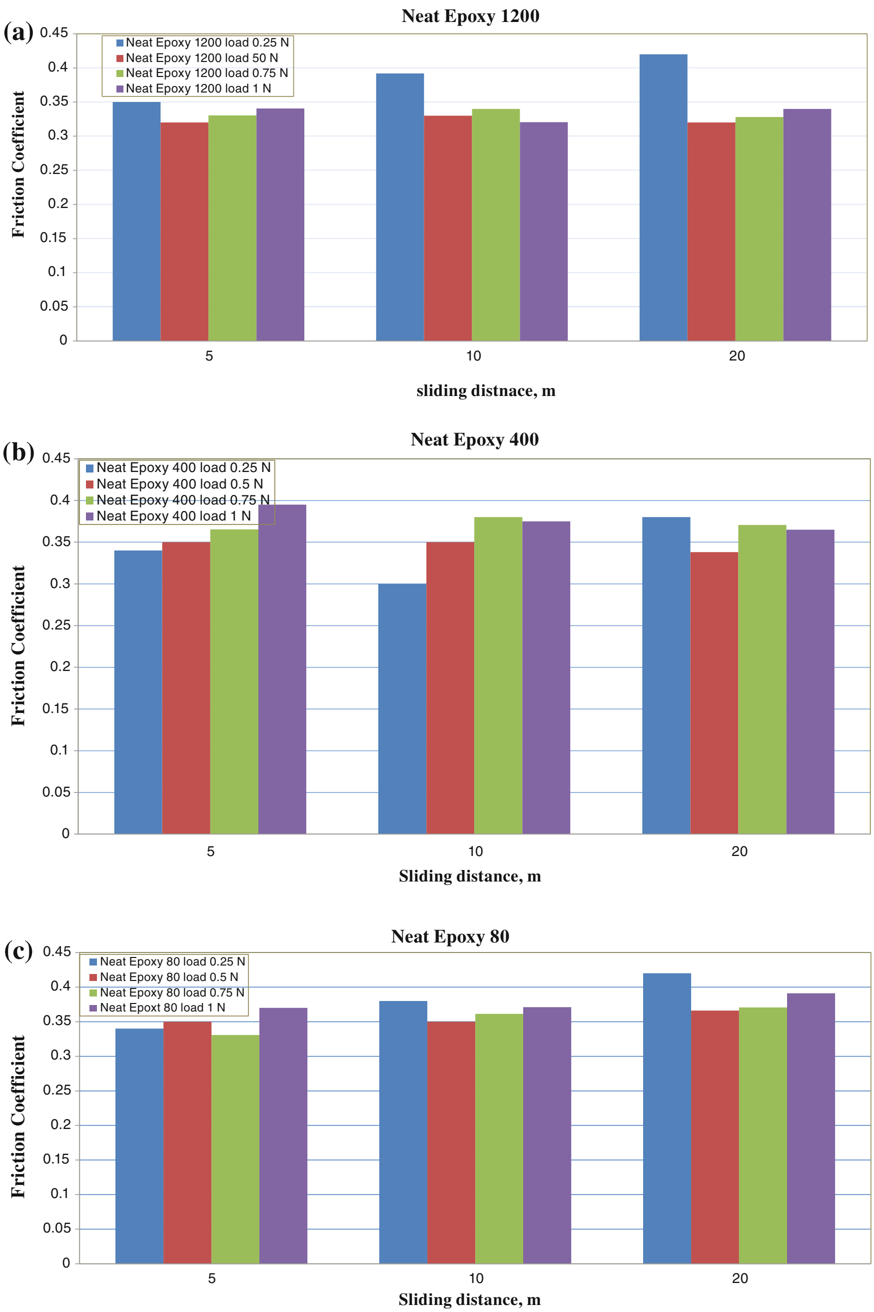


Fig. 10 Frictional performance of neat epoxy under different applied loads using different abrasive paper grades

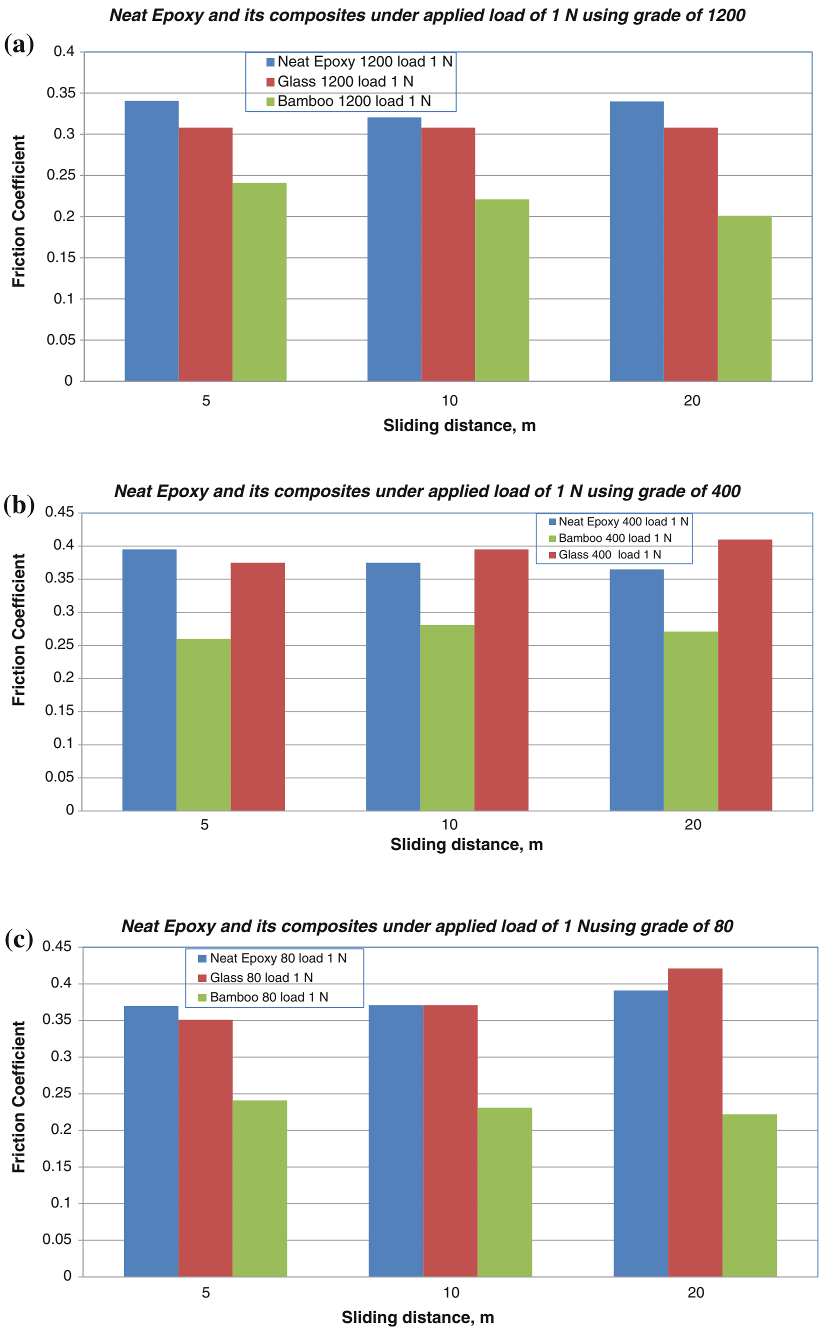


Fig. 11 Frictional performances for neat epoxy and its composites under applied load of 1 N using different abrasive paper grades

and Sharma et al. [13]. The results of the friction coefficient for all graphs show close values at all applied loads which is due to homogeneous asperities at contact. All charts show that the high values of the friction coefficient led to an increase in the wear rate of the neat epoxy in the rubbing area, which could be due to the increase in the interface temperature on the neat epoxy surface. It is believed that the presence of natural fibres such bamboo fibre on the neat epoxy surface might achieve better frictional behaviour as has been studied in recent research such as [17, 18].

3.2.7 Comparison of Frictional Performance of Neat Epoxy and Its Composites

Compared with the frictional performances of the BFRE composite, the GFRE composite and neat epoxy (NE) under an applied load of 1 N using different abrasive paper grades presented in Fig. 11a–c, each curve distribution demonstrates a different trend of friction coefficients. Overall, it can be seen that polyester composites reinforced with bamboo introduce better frictional behaviour than the others. The graphs demonstrate that the neat epoxy gives the highest frictional values, followed by the glass fibre epoxy composite. The main reason for the occurrence of damage features (such as high material removal) on the surface of the GFRE composite and the NE is the high values of their friction coefficient which led to increasing interface temperature on their surfaces. At higher applied load, epoxy composite reinforced with glass fibre exhibits a high friction coefficient compared to epoxy composite based on bamboo fibre. This gives it the potential for replacing synthetic fibres with natural fibres to reinforce polymeric composites for tribological and mechanical applications. The charts clearly demonstrate that the frictional performance for bamboo epoxy composite is better at higher applied loads except for the grade of 1200. This indicates that the surface roughness of the bamboo epoxy composite is less than the others, which produces low-interface temperature by friction leading to low wear and friction behaviour of the composite. Although the friction coefficient for the bamboo fibres recorded slight increase in value, the values are less compared to the other fibres.

This suggests that polyester composites reinforced with bamboo fibres introduce better frictional and wear performance compared to the other natural and synthetic fibres. This is due to the high interfacial adhesion of bamboo fibres with a synthetic matrix as mentioned in the wear performance of bamboo section. Many recent researchers have reported this, including [1, 4].

3.3 Surface Observation for Neat Epoxy and Its Composites

Figure 12 displays micrographs of the worn surfaces of bamboo fibre epoxy composite under different applied loads using different abrasive paper grades.

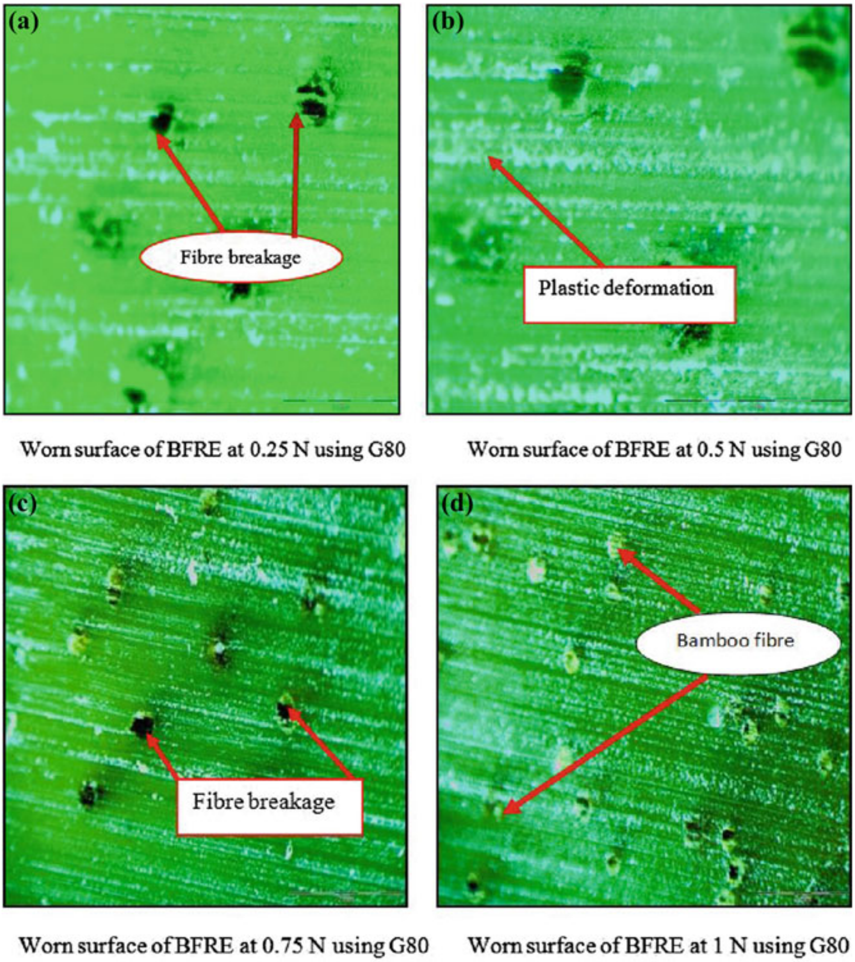


Fig. 12 Micrographs of the worn surface of the bamboo fibre reinforced epoxy under different applied loads using G80

Figure 12a shows that the softening process happened in the resinous areas and was associated with the shear loading. However, there is no trace of the pull-out of fibres on the composite surface during the rubbing process. In the case of grade of 80 and 400 (Fig. 12b, c), surface topography illustrates a clear plastic deformation on the composite surface, which is due to increased and distributed interface temperatures on the whole surface of the composite and to the increase in the surface roughness of these abrasive papers compared to the previous grade of 1200. All charts show

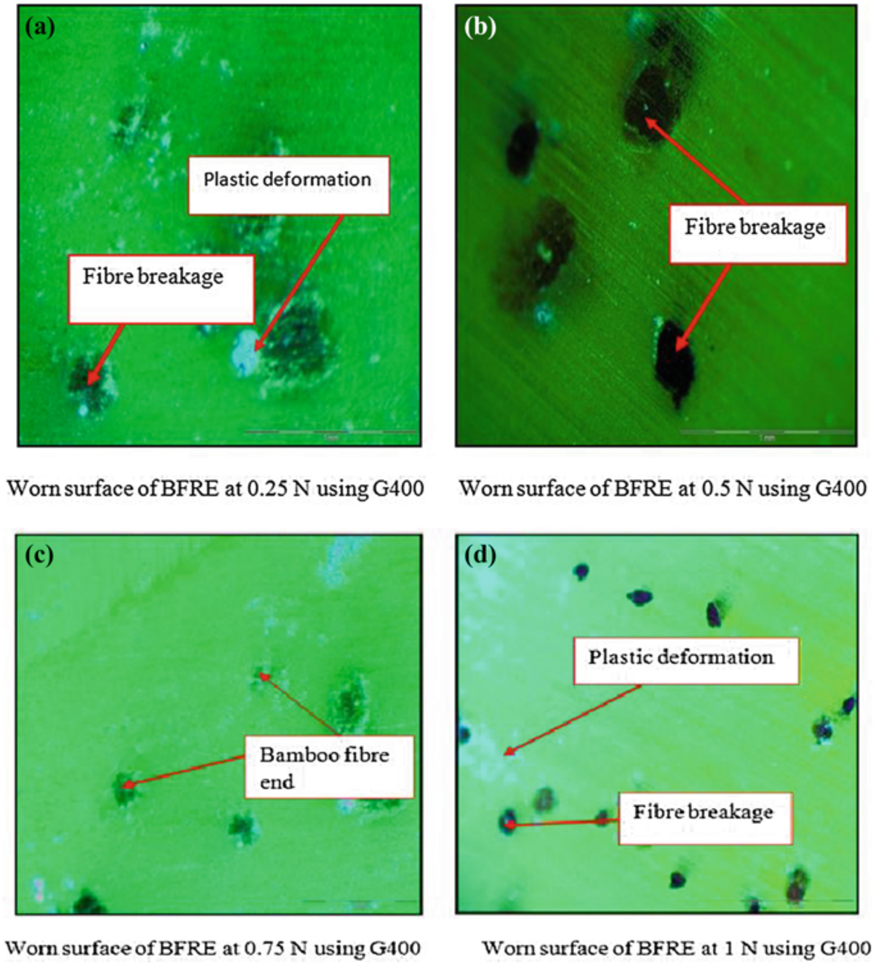


Fig. 13 Micrographs of the worn surface of the bamboo fibre reinforced epoxy under different applied loads using G400

that the bamboo fibre epoxy composite has better wear resistance. This could be due to the fibres being oriented perpendicular to the direction of the sliding surface.

In other words, the fibres have been able to resist the shear strength and carry the applied load outside the polyester area. Although peeling of fibres took place gradually which leads to detachment and breakage of fibres over time, this problem is solved by controlling the interfacial adhesion property of the fibre with the polyester matrix, as has been reported by Yousif et al. [19]. This indicates high

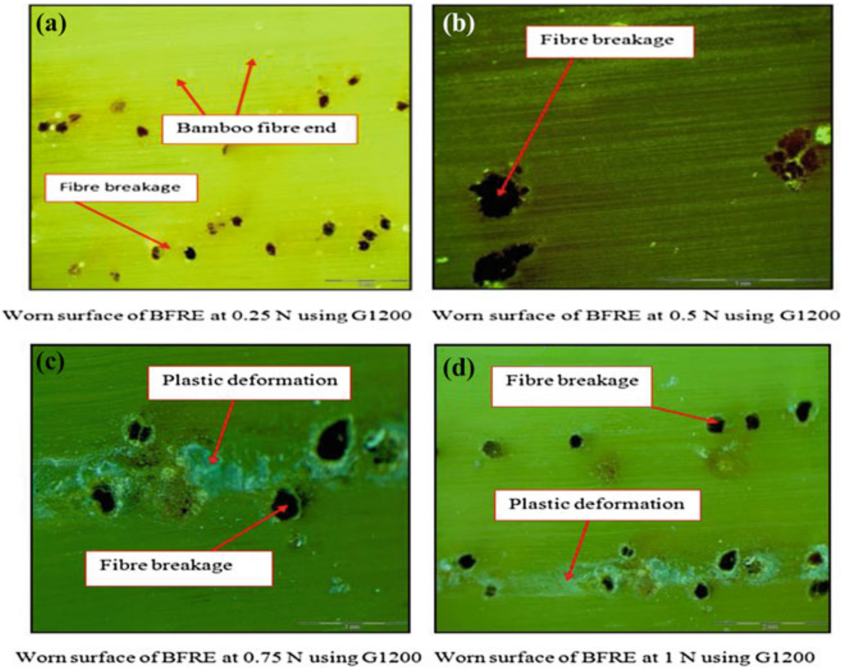


Fig. 14 Micrographs of the worn surface of the bamboo fibre reinforced epoxy under different applied loads using G1200

interfacial bond strength of bamboo fibres with the synthetic matrix. Some investigations (reported in the literature) have observed similar damage features on the composite surface when the polyester composite based on natural fibres was subjected to frictional force and heat which led to an increase in the interface temperature. They showed similar damages with kenaf [4], jute [1], and sugarcane [7]. These researchers recommend that further investigations be conducted to decrease the high frictional heat and force on the composite surface because they are considered to be the main reason for such damage. With regards to surface observation on the abrasive paper grades, the surface micrographs for all grades show that there is epoxy debris, and an epoxy patch can be seen on the abrasive paper surface as shown in Fig. 13a–c. This could be due to the high interface temperature on the composite surface which is caused by friction.

The micrographs of the neat epoxy surface under different applied loads using different abrasive paper grades are presented in Fig. 14a–c. All charts show that the surface micrographs of neat epoxy demonstrate softening and deformation of the epoxy. This could be due to the increase in the interface temperature on the surface

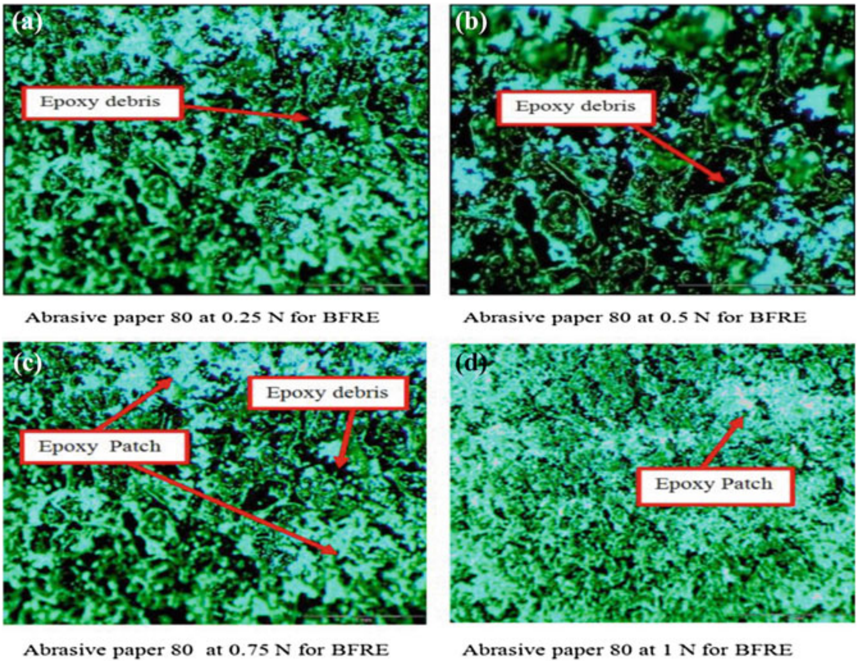


Fig. 15 Micrographs of the abrasive paper when the bamboo fibre reinforced epoxy tested under different applied loads using G80

of the epoxy when it is subjected to the applied load. This increase in interface temperature associated with the shear loading helps to create micro-cracks on the epoxy surface. At higher applied loads, the high amount of material removal can be observed in the neat epoxy. It can be also observed that areas of grooves and sharp asperities appear along travel track on the surface of the epoxy during the process of rubbing. This indicates the high weight loss of the epoxy surface which is considered one of many issues associated with neat epoxy (as mentioned at the frictional performance of neat epoxy section). Regarding the grade surface inspection, a similar observation about the neat epoxy can be seen in Fig. 15a–c.

Figure 16 shows the worn surface micrographs of glass fibre epoxy composite under different applied loads using different abrasive paper grades. Figure 16a shows that the worn surface of the glass epoxy composite is occurred in clear forms of the damages represented by plastic deformation, pull-out, detachment, and the breakage of the fibres which are due to the brittleness glass fibres. At grades of 80 and 400 (Fig. 16b, c), the ends of the glass fibre are exposed to the stainless steel counterface. This exposure subjects them to high shear loading which in turn causes

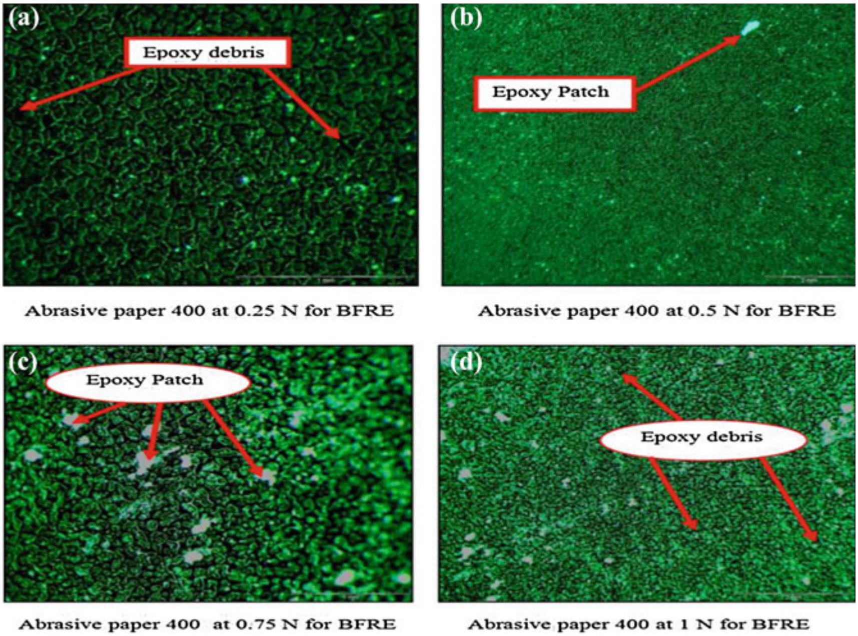


Fig. 16 Micrographs of the abrasive paper when the bamboo fibre reinforced epoxy tested under different applied loads using G400

the damage. At high applied loads, there is a removal of resinous areas followed by the pull-out of the fibres. This could be due to weakness in the interfacial bonding between the fibre and the polyester matrix. Similar results have been reported for polyester composites reinforced with glass fibre [3, 9]. In general, the micrograph of the worn surface of the glass epoxy composite shows different damage features for the three types of abrasive papers for all applied loads. The exposed fibres may contribute towards the increase in the material lost from the composite surface by the increasing coefficient of friction as mentioned in the previous frictional performance of glass, which in turn increases the wear rate. In regards to surface observation on the abrasive paper grades for the glass epoxy composite under microscope, similarly to other findings reported with bamboo epoxy composite and neat epoxy and presented in Fig. 17a–c.

A sample of micrographs of the worn surfaces for the neat epoxy and its composites under an applied load of 1 N using abrasive paper grade of 400 are presented in Fig. 18. For the neat epoxy, plastic deformation can be seen on the epoxy surface in the sliding process, i.e. a softening process for polyester resin occurred in response to the interface temperature. The effect of the interface

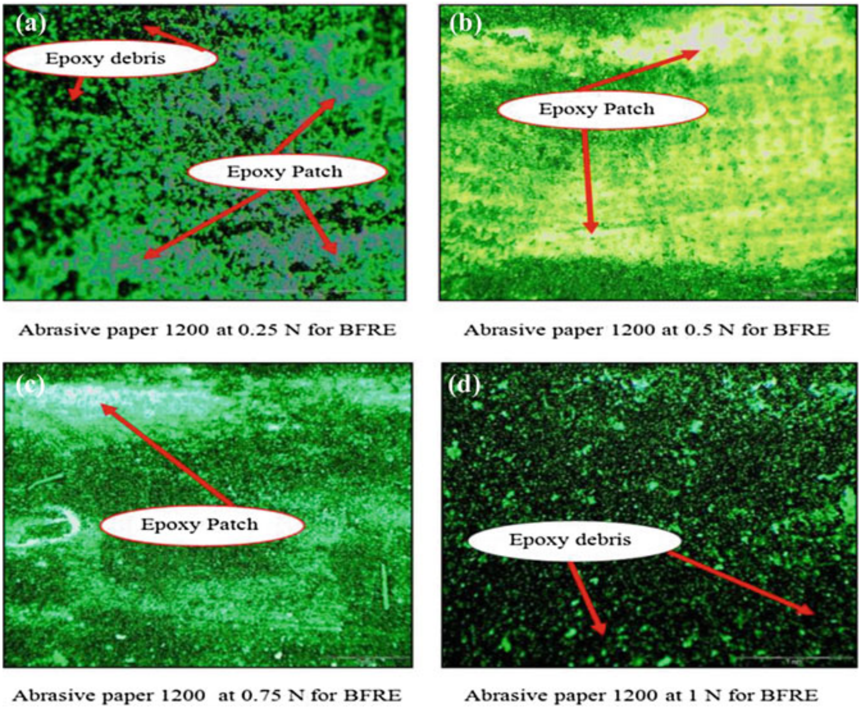


Fig. 17 Micrographs of the abrasive paper when the bamboo fibre reinforced epoxy tested under different applied loads using G1200

temperature on material removal is due to the friction loading causing more damage on the epoxy surface. In the bamboo epoxy composite, similar results can be observed. The softening process happens to the resinous areas which lead to the exposure of the bamboo fibre to the counterface causing the breakage of fibres over time (as mentioned in the optical microscopy of bamboo fibre section). However, the high damage occurring on the surface of glass epoxy composite can be seen under microscope. Of these damages, there are plastic deformation, material removal and pull-out of fibres when the composite is subjected to the applied load of 1 N.

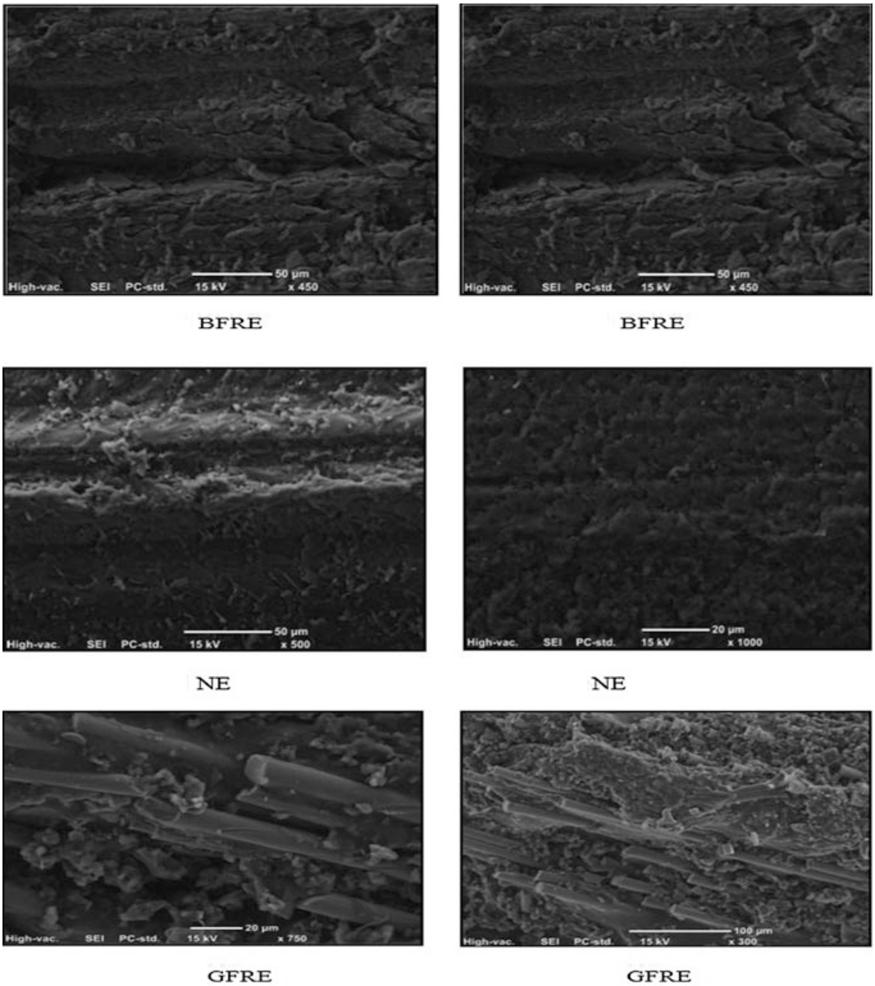


Fig. 18 Micrographs of the worn surface of the neat epoxy and its composites

4 Conclusions

In this study, a new epoxy composites based on the bamboo fibres were developed. The abrasive wear and frictional behaviour of the new composites were investigated with the neat epoxy and glass/epoxy composites. Different parameters and abrasive paper grades were used in the experiments. Based on the finding of the work, few points can be concluded as follows:

- The operating parameters (load and sliding distance) have great influence on the wear and frictional performance of all the composites. Steady state of the wear rate can be reached after few metres of the sliding distance with greater applied loads $\gg$ 0.5 N.

- SiC grades have equal influence on the wear and frictional behaviour of the composites with the operating parameters. At greater SiC grades, the wear rate reduces and the friction coefficient showed slight reduction as well. This was mainly due to the coverage of the high-grade SiC papers with the patches of the soft part (composites) which in turn generated a film on the SiC papers converting the abrasive into adhesive wear. This reduces the interaction between the asperities and then reduces the friction as well.
- Comparing the three developed composites (neat epoxy, bamboo/epoxy and glass/epoxy), bamboo fibres introduced better reinforcement to the epoxy in term of abrasive wear behaviour since it exhibited low wear rate compared to the glass and neat epoxy. It seems the softness and the strength of the bamboo fibres assisted to improve the surfaces during the rubbing and reduced the abrasiveness of the SiC papers. However, due to the fact that glass fibres are abrasive material, high wear rate achieved with the glass/epoxy since two high abrasive surfaces are in interaction which led to high material removal.

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