Wear properties of nanoclay modified basalt fibre composites under dry adhesive sliding, two-body abrasive, and slurry pot erosive

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Abstract
This paper reports the effect of 1.0 wt%, 3.0 wt% and 5.0 wt% nanoclay loadings on specific wear rate properties of basalt fiber reinforced polymer (BFRP) composites. The specific wear rate properties of the BFRP composites were analyzed at three different wear conditions, i.e., dry adhesive sliding, two-body abrasion, and slurry pot erosion in which the composites slide against smooth steel, rough silicon carbide, and medium-coarse sand mixture, respectively. The operating parameters for the wear tests were set at 30 N load, 300 rpm speed, and 10 km distance. The results demonstrated that the addition of nanoclay effectively enhanced the adhesive and erosive wear properties of BFRP composites. In adhesive wear properties, BFRP containing up to 5.0 wt% (EP/BF/5NC) marked 31.73% improvement when compared to the pure system, whereas, under erosive wear condition, the wear rate reduced by up to 51.12% when 1.0 wt% of nanoclay was added to EP/BF. As the nanoclay content increases, the wear rate exhibited improvement as indicated by reduction of erosive wear resistance. In contrast, nanoclay incorporation deteriorated the abrasive wear properties of BFRP. The abrasive wear rates reduced as nanoclay content increased, for example, the incorporation of nanoclay up to 5.0 wt% deteriorated about 101.94% when compared to pure EP/BF. The morphology of worn surfaces was evaluated using scanning electron microscopy (SEM) to study the wear behavior of the nanoclay modified BFRP composites. It concluded that nanoclay incorporation exhibited significant influence on wear properties of the polymer composites depending on the wear environment condition.

Keywords Basalt fiber · Polymer composites · Nanoclay · Adhesive wear · Abrasive wear · Erosive wear
Introduction

Polymer matrix composites are widely used as component in various engineering applications due to its high strength, high-stiffness, light weight, ease of shaping and fabrication, low cost, and high corrosion resistance properties [1–4]. Recently, these materials are also increasingly being selected as sliding materials, such as bushing, journal bearing, rollers, seals, gears, cams, wheels, and clutches that usually employ in automotive and aerospace fields [3, 5, 6]. This is mainly owing to their superior lubrication property, mechanical properties, chemical resistance, and damping characteristic that omit the usage of external lubricant [5, 7]. These qualities can provide maintenance-free operations in contrast to metallic materials especially when subjected to dry friction conditions [8, 9]. Depending on the selected reinforcement/filler, polymer composite materials present excellent friction and wear characteristics, which enable them to perform even at severe conditions that usually difficult to get with metals, ceramics, or neat polymers [4, 5, 10, 11]. In general, their acceptability in practical applications is determined by their mechanical load carrying capacity and specific wear rate, both can be improved by addition of hard different fillers, solid lubricants, nanoparticles, and fibers [5, 10].

The latest development of polymer composite technology is the combination of reinforcing fibers and nanoparticles, in which this so-called advanced polymer composite or hybrid composite can enhance tribological properties of the polymers significantly [6–8, 12–16]. The combined effect of nanoparticle and fiber provide positive effects to the composites where they can efficiently operate under many severe circumstances than the composite with nanoparticle or fiber alone. The reinforcing nanofillers enhance load carrying capability of matrix, enhance adhesion between reinforcing fiber and matrix, and protect the fibers by ‘rolling effect’ [7, 13]. Some studies had shown that the incorporation of nanoscale filler such as nanoclay [14–16], TiO₂ [17], SiO₂ [3, 18], ZrO [19], Carbon nanotubes [7, 20, 21] and Al₂O₃ [12, 22] in polymer matrix has led to improvement of tribological properties. A smaller particles size, especially nanofiller, has much higher specific surface area that provides huge interface area between nanofiller and matrix. This eventually promotes a better stress transfer, better bonding, and very strong interaction between filler and matrix [9, 19, 23]. Besides that, the presence of nanofiller and its interaction with rubbing surfaces is an important factor that affects the development and characteristic of transfer film during sliding wear [13, 17, 24].

Research on composites under adhesive wear or commonly called dry sliding has been conducted vastly since polymer composite is a popular sliding component. Research on epoxy nanocomposites was done by Zhang et al. [23]. The nano-SiO₂ was incorporated into epoxy matrix and tested under dry sliding wear. It was found that the nanofiller addition has negative effect on the wear properties of epoxy up to a critical value of 10 wt%, although its mechanical properties were improved proportionally with nano-SiO₂ content. However, at 20 wt% nano-SiO₂ content the wear properties of epoxy started to improve. Another research
on advanced/hybrid polymer composite was done by Guo et al. [13], Rajini et al. [16], Zhang et al. [7], and Chang and Friedrich [17] have reported a similar finding where nanofillers exhibit positive impact on wear properties of FRP composites. It was concluded that presence of nanofiller acted as lubricant that promoted stable and uniform transfer film and as spacers that reduced adhesion between contact surfaces, which consequently reduced stress concentration on individual fibers in contact region.

Under abrasion wear condition, there are two types of wear, i.e., two-body abrasion and three-body abrasion wear. Suresha et al. [14] conducted three-body abrasion on nanoclay filled epoxy composite and found that nanoclay incorporation has exhibited better abrasive wear-resistant, hardness, tensile strength, and modulus with nanoclay content up to 5.0 wt% as compared to neat epoxy, owing to its good dispersion and wetting with epoxy matrix, similar with finding by Lam and Lau [15] in research conducted under two-body abrasion of nanoclay filled epoxy composite. Research conducted on advanced polymer composite also revealed positive effect of fillers incorporation such as nanoclay [25], nanosilica [18], carbon nanotubes [21], and graphite [6] on two-body abrasive wear properties of FRP composites, where the filler reduced surface damage from micro-cracking to micro-cutting mechanism.

A number of research was also done under erosive wear condition. Research conducted on GFRP composite under slurry pot erosion revealed that glass fiber and incorporation of nanoclay, nanosilica, and carbon nanotubes in epoxy matrix have improved its erosive wear-resistant [18, 21, 25]. Other researchers studied the impact erosion wear behavior at different operation parameters such as impingement angle, impact velocity, particle size, and stand-off distance using Taguchi’s method. Joshi et al. [22], Sridhar et al. [26], and Mahesha et al. [27] revealed that incorporation of Nanoclay, Al2O3, and NanoTiO2 have improved the erosion wear resistance of FRP composites.

However, since friction and wear are not real material properties, rather they are responses to dynamic tribo-system governed by sliding parts [23, 28], many researchers were conducted experiments with specific testing parameters such as load, pressure, velocity, time, etc. and materials to mimic real-life applications, as they can profoundly alter wear behavior of the composites [6]. There are five main types of wear, for instance abrasive, adhesive, erosive, fretting, and fatigue wear. Most dominant wear mechanism is abrasive wear as it contributed to almost 65% of total cost of wear in industrial applications [6, 14].

From the previous study, it has been proven that the presence of nanofiller improves various mechanical and wear properties of polymer nanocomposite and fiber reinforced polymer composites. Align with the concept of green tribology, which introduced by World Tribology Congress (WTC), this study aims to use natural mineral-based fiber reinforcement material, i.e. unidirectional basalt fiber, and mineral based filler, called as nanoclay, for the fabrication of fibre reinforced polymer composites. In future, this composite material will be used in various tribology applications. Up to date, the evaluation of tribological behavior of nanoclay filled basalt fiber under various wear conditions is still inadequate and limited data are reported in literature. In this study, three (3) different nanoclay contents, i.e., 1.0 wt%, 3.0 wt%, and 5.0 wt%, of nanoclay are dispersed into epoxy
resin using three-roll milling before incorporated with basalt fibers. The specific wear rates of EP/BF and EP/BF/NC composites are investigated under three (3) different condition, namely dry adhesive sliding, two-body abrasion, and slurry pot erosion and also three (3) different rubbing medium, i.e. smooth steel, rough silicon carbide, and medium-coarse sand mixture. The effect of nanoclay content on tribology behavior of basalt fiber reinforced polymer composites in various wear conditions and rubbing medium is comprehensively discussed.

**Experimental work**

**Materials preparation**

Epoxy resin and hardener (Miracast 1517; density:1.13 g/cm³) were supplied by Miracon (M) Sdn. Bhd. Miracast 1517 epoxy resin is a low viscosity laminating resin that can produce high-performance composite structure. Miracast 1517 B is an amine-curing agent that provides curing at room temperature. The mixing ratio was set at 100:30. Basalt fibers (BF) in unidirectional roving form, which has a density of 2.65 g/cm³, filament diameter of 9–15 μm, tensile strength of 1.96 GPa, tensile modulus of 94.77 GPa, and maximum elongation of 1.84%, was supplied by Haining Anjie Composite Material Co. Ltd. Montmorillonite (MMT) clay particles of type Nanomer I.28E, which has an average particle size of 8–10 μm and a density of 1.9 g/cm³, was supplied by Sigma-Aldrich, USA. The surface of MMT clay was modified with 25–30 wt% trimethyl stearyl ammonium.

The nanoclay-filled epoxy was produced by mixing nanoclay of desired weight percentage (1.0, 3.0, and 5.0 wt%) into epoxy matrix using manual mixing technique for 5 minutes and subsequently using a high shear three roll mill machine until a homogeneous, clear, and transparent form of nanoclay-epoxy paste was obtained. The three-roll mill machine uses the concept of shear force and heat to reduce the viscosity of epoxy and to disperse nanoclay uniformly in the matrix. The FRP composites were then fabricated using conventional filament winding and wet hand layup method. Aluminum frame plates with dimension of 350 mm x 240 mm were prepared to wind the fiber with fixed content of 15 vol%. Nanoclay-filled epoxy was distributed evenly onto the frame using roller. The frame was compressed with 10N weight to ensure flat surface and thickness before it was left to cure for 24 hours at room temperature. After curing, the fabricated frames were cut into specific sample sizes in accordance with ASTM standards as specified in Sects. 2.2 and 2.3. At least five samples were tested for each material system. The composition and designation of the composite systems are listed in Table 1.

**Density and hardness tests**

The density of fabricated specimens was determined using density balance based on Archimede’s principle in distilled water. The specimens were prepared in accordance
with ASTM D792. Hardness test was conducted to determine the hardness of the composite specimens using Instron A654 R Rockwell Hardness Tester machine following ASTM D785-08 standard. The Rockwell type R (HRR) used minor load of 10 kg, major load of 60 kg, and 12.7 mm diameter steel ball indenter.

Wear testing procedure

Dry adhesive sliding

Dry unidirectional adhesive sliding wear test was performed by using TR-20LE model pin-on-disc (POD) tribometer in accordance with ASTM G99-95a standard. Fig. 1 shows the schematic illustration of the POD tribotest. The specimen was cut into disc shape of diameter 76 mm and thickness of 4 mm, while the pin used was 10 mm diameter GCr15 stainless steel pin with hardness of HRC62 ± 2. Prior to testing, the steel pin was polished against abrasive papers to ensure surface roughness Ra of about 0.1 μm. The operating parameters were fixed at 30 N load, 300 rpm speed, and 10 km distance under dry condition at room temperature. The initial and final weight of specimens was measured in accuracy of ± 0.01 mg using precision balance. At least five samples were tested for each material system. The specific wear rate (Ks) is then calculated from following equation:

\[
K_s = \frac{\Delta m}{L \times F_N \times \rho} \left( \frac{\text{mm}^3}{Nm} \right)
\]

where \(\Delta m\) is the mass loss (g) of specimen, \(\rho\) is density of specimen (g/mm\(^3\)), \(L\) is the distance travel (m), and \(F_N\) is the normal load applied (N).

Table 1 Composition and designation of composite systems

| Composites                        | Designation |
|-----------------------------------|-------------|
| Epoxy + Basalt fibre              | EP/BF       |
| Epoxy + Basalt fibre + 1.0 wt% nanoclay | EP/BF/1NC  |
| Epoxy + Basalt fibre + 3.0 wt% Nanoclay | EP/BF/3NC  |
| Epoxy + Basalt fibre + 5.0 wt% Nanoclay | EP/BF/5NC  |

Fig. 1 Pin-on-disc configuration under dry adhesive sliding wear test
Two-body Abrasion

Two-body abrasion wear test was performed using TR-600 model abrasion resistance tribometer (ART). Fig. 2 shows the schematic illustration of the ART tribotest. The specimen was cut into disc shape of 125 mm diameter and 5 mm thickness. The disc was in contact with two vitrified bonded silicon carbide abrasive wheels, grade 46 (medium-coarse). Before each test, the wheels were cleaned by using dry brush to eliminate any dust. The operating parameter was fixed at 30 N load, 300 rpm speed, and 10 km distance at room temperature. The initial and final weight of specimens was measured in accuracy of ± 0.01 mg using precision balance. At least five samples were tested for each material system. The specific wear rate (Ks) is then calculated using Eq. (1).

Slurry pot erosion

Slurry pot erosion test was done by using TR-40 model slurry erosion (SE) tribometer. Figure 3 shows the schematic illustration of the SE tribo test. The specimen was cut into rectangular shape of dimension 75 mm × 25 mm with thickness of 5 mm. A mixture of medium course (size ranged from 0.2 mm to 0.63 mm) sand and water was mixed in a pot as slurry media. The surface of specimens was in contact with sand particles that caused erosion on the surface specimens. Tests were carried out at 300 rpm speed and 10 km distance at room temperature. The pot was placed in a water bath to maintain surrounding temperature. The initial and final weight of specimens was measured in accuracy of ± 0.01 mg using precision balance. At least
five samples were tested for each material system. The specific wear rate (Ks) is then calculated from Eq. (2).

\[
K_s = \frac{\Delta m}{m \times \rho} \left( \frac{mm^3}{g} \right)
\]

where \(\Delta m\) is the mass loss of specimen (g), \(m\) is mass of erodent (g) used and \(\rho\) is the density of specimen (g/mm\(^3\)).

**Morphological observation**

Transmission electron microscopy (TEM-Tecnai 120KV BioTwin) was used to examine the dispersion of MMT clay within epoxy matrix. After the test, the worn surfaces were coated with a thin layer of platinum and then examined using HitachiTM3030 Plus scanning electron microscope. At the end of tests, the surface roughness and morphologies of worn surfaces were examined using Mitutoyo Surftest SV-500.

**Results and discussion**

**Density and hardness properties of the composites**

Table 2 listed the calculated values of density and hardness of the composites. The density values are used in Eqs. (1) and (2) to determine the specific wear rate of composites.

**TEM evaluation of MMT clay dispersion within epoxy resin**

The dispersion state of 1.0 wt%, 3.0 wt%, and 5.0 wt% nanoclay in epoxy matrix are shown in Fig. 4. The images show distinct regions of nanoclay-rich region (dark) and resin-rich region (light). Nanoclay platelets have dispersed uniformly in all figures showing that epoxy matrix has flowed in between the adjacent platelets, presenting intercalated and exfoliated structure of epoxy-clay nanocomposites. The gap between two adjacent platelets that are more than 2.4 nm but less than 8 nm, showed intercalated structure, while gap more than 9 nm showed exfoliated structure. As

| Composites   | Density (g/cm\(^3\)) | Hardness (HRR) |
|--------------|-----------------------|----------------|
| EP/BF        | 1.324 ± 0.009         | 119.50 ± 0.41  |
| EP/BF/1NC    | 1.240 ± 0.008         | 121.58 ± 0.70  |
| EP/BF/3NC    | 1.242 ± 0.014         | 122.15 ± 0.44  |
| EP/BF/5NC    | 1.247 ± 0.006         | 121.63 ± 0.34  |
can be shown in Fig. 4, there is no sign of tactoids present, even at high nanoclay content.

**Wear behavior of composites**

Figure 5 shows wear volume (ΔV) trend of the composites under three different wear conditions with respect to sliding distance. All curves show almost similar trend with sharp increase at first 2 km travel distance, called run-in stage. The increment then reduced as travel distance increased further, called steady-state stage. The curve shows that the composite experienced a transition of initial high wear rate to steady-state at a low rate, which is typical for polymeric materials as also reported by K. Kato and K. Adachi [29]. Under dry adhesive sliding Figure 5a, the wear rate reduced to steady-state after approximately 2 km distance due to formation of transfer film that is believed to be developed during the run-in stage. Transfer film is very common yet very important factor that affects wear rate of adhesive wear for polymeric material. The ability of polymer to form transfer film and the structure of transfer film itself affects the wear rate of a composite as well as its wear mechanism [6, 10, 23, 30]. Under abrasion sliding,
Fig. 5 Typical trend of sliding performance of polymer composites against time under a dry adhesive sliding, b two-body abrasion and c slurry pot erosion wear
Figure 5b, the decreased increment of wear rate captured as distance increase was due to the fact that the abrasives grit become smoother and less effective than at the beginning of test where the abrasive grit was still fresh [31]. As described by Chauhan and Thakur [9] and Napisah et al. [20], the increment at initial part is due to different surface roughness of specimen and counterface, which allow the strong interlocking thus remove a lot amount of specimens. Under slurry erosion sliding, Fig. 5c, the thermal changes in slurry pot are believed to regulate after the run-in stage at first 2 km of sliding distance that resulted in higher mass loss at beginning test run.

Figure 6 shows specific wear rate, $K_s$ of composites sliding under dry adhesive sliding for 10km sliding distance. EP/BF composite attained highest wear rate value of $0.01421 \times 10^{-2}$ mm$^3$/Nm. Wear rate was found to be improved with incorporation of nanoclay. The sequence of wear rate for all FRP composites from lowest to highest is EP/BF/5NC, EP/BF/3NC, EP/BF/1NC, and EP/BF composite. The lowest wear rate of $0.0097 \times 10^{-2}$ mm$^3$/Nm recorded by EP/BF/5NC composite specimens marked 31.73% improvement from its pure state. Each constituent embedded into the epoxy matrix plays different role in improving wear resistance of the composite. The fiber increases mechanical properties of epoxy matrix, acting as main reinforcement to reduce wear rate significantly, while nanoclay acted as solid lubricant and generate transfer film thus reducing friction during sliding [32]. The effective of the nanoclay addition as solid lubricant can be supported by the SEM images of addition 5.0 wt% nanoclay, (EP/BF/5NC), as can be seen in Fig. 9, which present the smooth surface as compared to without nanoclay adhesion, (EP/BF). Besides that, nanoclay also acted as effective barrier to prevent large-scale fragmentation of epoxy matrix by steel counterface [6, 9].

Figure 7 shows specific wear rate, $K_s$ of composites sliding under two-body abrasive wear for 10km sliding distance. The lowest wear rate is shown by EP/BF composites at $0.07409 \times 10^{-2}$ mm$^3$/Nm, while highest wear rate is shown by EP/BF/5NC at $0.149 \times 10^{-2}$ mm$^3$/Nm. The sequence of wear rate from lowest to highest is; EP/BF, EP/BF/1NC, EP/BF/3NC, and EP/BF/5NC composites. The wear rates worsen further as nanoclay content increased to 5.0 wt% with 101.94% deterioration from its pure state. This might be due to three-body abrasive wear, where the high content of nanoclay that ploughed out of epoxy matrix has acted as abrasive and slide between the surface of composite and abrading roller, leading to further matrix

![Fig. 6 Specific wear rate of composites under dry adhesive sliding](image-url)
damage and fiber removal. Besides that, it also believed that the surface topography of the composites might increased the intensity of the asperities when add the nanoclay, which allows to grind specimen when attached to coarse SiC. As can be seen in Fig. 10, the worn surface for EP/BF/5NC shows the specimen groove and fractured basalt fibers as wear mechanisms occurred. In three-body abrasive wear, there is four wear mechanisms which are micro plowing, micro-cutting, micro-cracking, and micro fatigue, which occur during wear [20, 33, 34].

Figure 8 shows specific erosion rate, $K_s$ of composites sliding under slurry pot erosive wear for 10km sliding distance. The highest wear rate exhibited by EP/BF composites charted $3.4432 \times 10^{-2}$ mm$^3$/g. When nanoclay was added, the wear rate improved up to 51.12% improvement corresponding to that of EP/BF composite, exhibited by EP/BF/1NC composite specimen with value of $1.6797 \times 10^{-2}$ mm$^3$/g. However, as nanoclay content was increased, the wear rate also exhibit increment, which indicated reduced erosive wear resistance. The sequence of wear rate from lowest to highest is; EP/BF/1NC, EP/BF/3NC, EP/BF/5NC, and EP/BF composites. The improvement was contributed by nanoclay addition, which served as energy barrier to prevent impact energy of sand mixture from penetrating into the surface of the composite. Therefore, the sand mixture was unable to penetrate efficiently into
the surface. However, the wear rate actually increased as nanoclay content increased, which might due to decrease adhesion between nanoclay and epoxy matrix. This then may lead to ineffective performance of nanoclay to reinforce the epoxy matrix. The effective of nanoclay as wear-resistant filler results also match the findings of other authors [16, 27].

**Worn surface morphology**

Figure 9 shows the worn surfaces of selected composites i.e., EP/BF and EP/BF/5NC, taken at the end of adhesive sliding test. During the adhesive wear test, the BFRP composites were slid against 10 mm diameter GCr15 stainless steel pin. The sliding direction of the counterpart is marked with the black arrowhead. The worn surface of the EP/BF, as can be seen in Fig. 9a was characterized by severe plastic deformation with visible microcrack and exposed fibers. Some of the fiber is still embedded in matrix, while some are removed, indicating fiber pull-out. There are also deep grooves visible on the matrix indicating severe cutting mode of harsh wear due to large size of material pull out that leads to its high wear rate value. Worn surface of EP/BF/5NC composite in Fig. 9b shows a smooth surface with very few microcracks. The fibers are only half exposed indicating high wear resistance of the composite. The microcracks in matrix propagate due to repeated and long period of shear loading, but still not detached from the matrix. Fatigue wear is the predominant wear mechanism, instead of severe abrasive wear. It can be concluded that in adhesive wear condition, the smooth surface and less fiber exposed when added nanoclay supported the obtained result, where the addition of nanoclay resulted in reducing specific wear rates. As discussed earlier, the nanoclay acted as effective barrier, solid lubricant and generate transfer film during sliding which prevent the composites from wearing [6, 9, 32].

Figure 10 shows the SEM micrographs of worn surface of EP/BF and EP/BF/5NC composites after travel for 10km distance under SiC abrasive roller. The mechanism...
of the abrasive wear such as micro plowing, micro-cutting, micro-cracking, and micro fatigue had been observed on worn surface of both EP/BF and EP/BF/5NC composites. As for EP/BF, the SEM image shows severe damage to the matrix with some fiber visible and exposed. The fibers are still intact in matrix with no fiber pull out indicating good adhesion between matrix and fiber. When nanoclay is added, the wear rate becomes worse with more material removal from the composite as can be seen in Fig. 10b, which represents worn surface image of EP/BF/5NC. The SEM image illustrated mild matrix damage with more fiber exposed and protruded out of matrix. Severe microcracks and deep grooves are visible initiated around the fibers caused by plowing and cutting action of abrasive rollers. The grooves formed are wide and deep compared to EP/BF composite, where the microcracks propagated and connected then fractured out after repeated shear loading. The microcracks surrounding the fiber indicating brittle fatigue wear of the matrix. There are many factors could affect wear performance such as working or test parameter, the structures of the composites, material used, type and size of filler and etc. [20]. In this study, even though the dispersion of nanoclay considers homogeneously dispersed, as evidence in Fig. 4, the adhesion bonding might be reduced as nanoclay content increases and the structure of the composite might be different as compare to with and without nanoclay. Therefore, these factors give contrast wear performance in different wear conditions.

Figure 11 shows SEM micrographs of EP/BF and EP/BF/5NC composites after exposed to coarse sand for 10km travel distance. For worn surface of EP/BF composite, the matrix shows severe damage at most areas, with fibers already exposed. There are cracks visible surrounding the exposed fiber resulted from removal of subsurface from cutting action of erosive. The matrix deformed is more severe than matrix deformation when add nanoclay. With addition of nanoclay, EP/BF/5NC, the matrix show less severe erosion, with only small portion of fiber exposed (Fig. 11b). The microcracks are visible at most area, already propagate towards each other leaving small groove, pit, and craters behind. Nanoclay incorporation has aid in
improving wear resistance of composite by changing abrasive wear to mild fatigue wear, which eventually reduces the wear rate of BFRP composites. In addition, the fibers are still intact in matrix indicating strong fiber-matrix adhesion that resulted in very less fiber-matrix debonding which also contributing to good wear properties.

Figure 12 shows the surface roughness, $R_a$ of composites at end of all wear tests. All composites’ initial $R_a$ was maintained at 0.10–0.20 μm. At the end of tests, the worn surfaces’ $R_a$ was found to be higher. The high $R_a$ indicated that the surfaces are rough, and vice versa. Highest $R_a$ cluster exhibited by composite underwent dry adhesive wear test, while lowest was erosive wear test. The trend shown infers that the worn surfaces were a lot rougher after dry adhesive wear compared to worn surfaces of composites underwent abrasive and erosive wear, although their wear rate wasn’t that high if compared to abrasive wear rate. The sequence of $R_a$ between composites in each test was also not consistent with their wear rate result.
The relationship between wear rate and $R_a$ of composites needs in-depth research in the future to understand its behavior and provide any conclusion.

**Conclusions**

Wear properties of epoxy polymer reinforced with mineral basalt fiber and nanosized clay filler were successfully evaluated under different wear conditions; dry adhesive sliding, two-body abrasion and slurry pot erosion wear. All composite experience a run-in stage at first 2 km sliding distance before reaching their steady-state stage which is typical for polymeric material sliding against fresh/new counterface. The presence of nanoclay filler exhibits positive influence on dry adhesive wear and slurry erosive wear resistance of BFRP composite as it resulted in 31.73% and 51.12% improvement, respectively. The wear mechanism changed from abrasive wear to fatigue wear with the presence of nanoclay. Two-body abrasive wear property did not improve with the presence of nanoclay, instead, it deteriorates drastically up to 101.94% compared to EP/BF composite. In short, nanoclay-filled BFRP composites can favor application that needed low wear that operates in adhesive and erosive environment, for example, bearings, bushings, pipelines, and chute liners. However, in abrasive environment, nanoclay incorporation can only benefit in applications that needed high wear, usually as sacrificial materials.

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**Declarations**

**Conflicts of interest** The authors declare no conflict of interest.

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