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# Investigations on Dry Sliding Wear Behavior of Hybrid Long Sisal-Jute Fibers Polymer Composites

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**Abstract**: The study aims to analyze the synergistic effect of hybrid fiber reinforcements on wear resistance of epoxy based natural fiber reinforced polymer composites (NFPCs). The study employed jute and sisal fibers as reinforcements. Two distinct reinforcements were incorporated in equal percentages to each type of composite sample. Five distinct composite specimens were identified as follows: NFPC-8 (containing 4% sisal and jute fibers each), NFPC-16 (containing 8% sisal and jute fibers each), NFPC-24 (containing 12% sisal and jute fibers each), NFPC-32 (containing 16% sisal and jute fibers each), and epoxy (EP) (containing 0% reinforcements). The hand layup technique was used for developing hybrid natural composites. In accordance with ASTM G99, pin-on-disc wear test rig was used for the dry sliding wear tests. The effect of applied load and sliding velocities on wear volume loss and specific wear rate was studied. The obtained results indicated that wear volume and specific wear rate are significantly affected by applied load and sliding velocity. NFPC-32 composite exhibited minimum wear loss and specific wear rate compared to other specimens. Besides, wear loss and specific wear rate were found to increase with the increase in applied load owing to the high contact stress at counterface during sliding. Further, wear volume and specific wear rate have increased with the increase in sliding velocity. It may be due to the fact that, high shearing force has resulted in sheared transfer layer at higher velocity. Worn surface analysis using scanning electron microscopy images shown the evidence of fragmented fibers and their pull out.

**Keywords**: epoxy resin; jute fiber; sisal fiber; natural composite; dry sliding wear; surface morphology

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## 0 Introduction

In mechanical industries, the natural fibers are used in the manufacturing of polymeric composites with epoxy as matrix. The usage of polymer composite over the metal based one is very much significant because of high specific strength, ease of processing, low density, self-lubrication and aesthetic[1-2]. The automobile sectors are orienting towards the polymer composite due to their better mechanical, tribological and thermal response[3]. Recently, increased ecological awareness and sustainability concerns due to the use of synthetic ingredients in composite materials employed automotive and bio medical applications have shown the importance of natural reinforcements. Natural fibers have great attention due to their characteristics such as eco-friendly, availability, biodegradability and sustainability[2-3]. Owing to the bio-degradability, natural fibers are envisaged as a substitute to synthetic fibers in various engineering applications. Besides bio-degrability, they also offer considerable physical and mechanical properties meeting the demands of engineering applications[4]. Further, better properties are offered in addition to reasonably strong, lightweight, harmless to human health and the environment and flexible manufacturing methods. Thus, natural fibers reinforced composites are suitable to structural applications[5]. Natural fiber reinforced polymer composites (NFPCs) are widely used in several interior applications in automobile sector include trunk liners, door panels, seat back, dashboards and package trays as well as in constructional applications[6]. Bio-based fibers such as

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jute fiber, sisal fiber, ramie fiber, sisal fiber, drumstick fibers, basalt fibers, paddy straw fibers, pineapple leaf based fibers and many more were proved as potential reinforcing members in composite system to resist mechanical and tribological loading in their service life. Furthermore, fiber treatment with NaOH solution yields fiber better surface characteristics, which helps to achieve superior interfacial bonding between fibers and matrix[7]. Epoxy is widely used matrix in the polymer composite development because of its easy flow ability and good interaction with the reinforcing phase[8]. The impact of natural fibers on tribology of epoxy composite is a scientific interest for several researchers. The effects of various natural fibers on the dry sliding wear behavior of epoxy-based polymer composites have been studied.

Chaudhary et al.[9] studied the effect of sliding wear parameters on wear behaviour of Jute/Hemp/Flax reinforced hybrid epoxy composites. The fiber concentration in the composites was varied in the study. It was found that, hybrid fibers-based composites exhibit excellent wear resistance at different experimental conditions in comparison to neat epoxy polymer. The friction effects in terms of covalent organic frameworks (COF) have been declined due to higher hybrid fiber effect. The waste marble dust effect on wear characteristics of coconut fiber/ epoxy incorporated composites (FRCs) was reported by Bothiraj et al.[10]. The marble dust content and sliding velocity were found to be the most considerable factors for the improved wear resistance of studied hybrid composites. The impact of short jute fiber shows potential in increasing the wear characteristics of composite[11]. Gupta et al.[12] depicted that short ramie fibers and glass fibers influence on tribological property of polypropylene composite. They used short jute fibers and glass fibers for development of polypropylene composite using hand lay-up process. The study illustrated the influence of ramie fibers on wear characteristics by varying the velocity, load and interaction time. The short ramie fibers were more dominant over glass fibers in controlling wear loss of epoxy composites. Edoziuno et al.[13] reported the reinforcement impact of wood charcoal and periwinkle shell on the wear behavior of polyester composites and studied the impact of sliding distance, load and velocity. The composite reinforced by wood charcoal and periwinkle shell exhibited the enhanced wear resistance compared to pure polyester. Further, the COF was declined by 30% against neat polymer.

Toth et al.[14] presented the wear characteristic of natural fiber reinforced composites (FRCs) and used jute and basalt fibers as reinforcements. They showed that adding of fillers like polytetrafluoroethylene (PTFE) combinedly reduces wear loss of polyester and vinyl ester composites. The development of ramie/epoxy FRCs and their wear characteristics has been reported by Kumar and Anand[15]. They developed epoxy composites using ramie fibers up to 40 wt. % by varying in steps of 10 wt. % using hand-layup technique. They studied the effect of sliding velocity and load on wear characteristics for a known distance. The finding of the test shows that adding of ramie fibers effectively increases wear resistance. They found that wear resistance was increased by 70% at lower load (10 N) and 60% at a higher load (30 N). The COF is increased with increment in fiber loading. Mechanical and tribological characteristics of hybridized fibers have been reported by Venagayamoorthy et al.[16].

Long fiber reinforced thermoplastics shows the better performance, weight and cost reduction when compared to conventional thermoplastics. The composites were prepared by hand lay-up method by varying fiber percentage from 10 to 40 wt. % in steps of 10 wt. %. The impact of applied pressure (10, 20 and 30 N) on wear characteristics and friction has been investigated. It is found that 30 wt.% of fiber has shown the excellent wear resistance. Himalayan nettle/Bauhinia-vahlii fibers reinforced epoxy composite have been investigated [17]. The wear characteristics of composites were studied using Taguchi approach and the major factors for the wear phenomenon were presented. Kumar and Mer[17] have found that hybrid impact of these two fibers could significantly enhance wear resistance. Furthermore, the applied load is one of the major parameters for the preparation of wear model. Mahesh et al.[18] investigated the three body abrasive wear behaviour of jute/rubber green composite materials. The study suggested that, addition of jute in rubber in various combinations significantly improved the wear resistance. Though fiber breakage was the dominant wear mechanism, jute fibers addition was able to contribute towards yielding adhesive, subsequently progressive wear instead of drastic abrasion. The ceramic fillers effect on wear characteristics of jute-glass composites has been studied and reported by Borah and Samanta[19]. They studied the sliding wear as response of these materials against varying applied load and sliding velocities. The results have shown that the moisture is the significant factors for affecting the wear characteristics. Further, the impact of load is more governing compared to velocity. The combination of both ceramic filler and hybrid fibers plays vital role in increasing the wear resistance of composites.

Anandvel et al.[20] studied the mechanical and wear behaviour of rice husk microfibres and $ZrO_2$ extracted from Phyllanthus niruri incorporated hybrid vinyl ester composites. The study illustrated that, $ZrO_2$ bioceramic incorporation in combination with rice husk has significantly enhanced the mechanical properties and wear resistance of the composites. The role of $ZrO_2$ was vital in the improving the characteristics of composite materials. The effect of natural fibers on the wear has been discussed by Milosevic et al.[21]. Study indicated that wear of composites is affected by its ingredients, subsequently their volume fraction. The tribological response is function of applied load and velocity. It was concluded from Ref. [21] that, natural fibers possesses great potential as reinforcements of composites employed in tribological applications. The combined effect of jute, sisal and bagasse fiber on the wear characteristics of polylactic acid have been studied and reported by Yadav et al.[22]. They used 10 wt. % and 20 wt. % of fiber volume fractions for the processing. The findings have showed that wear characteristics have been increased. The tribological response of composite is better by the effective reinforcement of sisal fibers. The frictional coefficient reduces with the increases in volume fraction of these sisal fibers. One of the important limitations of natural fibers as reinforcements is their poor bonding characteristics as well as premature occurrence of debonding and microcracks during loading. Ref. [23] has proved that, it can be overcome by the hybridization of reinforcements instead to using a mono-type reinforcement of fibers. Another, significant limitation of natural fiber is their hydrophobic nature, due to the same they possess poor water absorption characteristics. Whereas, it was reported by Yorseng et al.[24], hybridization of reinforcements can help to achieve better resistance against degradation and water absorption. The hybridization of reinforcement in natural composites considerably improves the physical and mechanical properties of the composites owing to the dual fiber nature. Also, consequently due to their synergistic effect, combined with reduced void fraction and better interfacial adhesion. Thereby, superior surface integrity characteristics and improved crystalline structures was found to contribute in enhancing the physical and mechanical properties of hybrid natural fibers reinforced composites[25].

The literature survey reveals that, considerably good number of researchers have reported on the impact of fibers like jute, sisal, and ramie fibers on frictional and wear characteristics of epoxy composites. Based on the performance characteristics, natural fibers have good impact resistance and rigidity at elevated temperature range, dimensional stability and resistance to warpage. However, the investigation on the impact of long sisal fibers and long jute fibers which are the strength bearing members used for automobile applications is limited. Especially, hybrid impact of long sisal and jute fibers on wear characteristics of epoxy composite under different speed and loading conditions is minimal. Therefore, the influence of sliding velocity and ng load on the friction and wear characteristics of long jute and sisal/epoxy FRCs has been studied. The study´s novelty involves the impact analysis of combined effect due to incorporating sisal and jute fibers on two-body abrasion resistance of epoxy based composite system. In addition, the ability of synthetic fibers to resist the abrasion has been investigated. On the other hand, critical study is required for natural fibers about abrasion wear. Further, effect of abrasion particle size will define the abrasion wear. The mechanism of wear transformation, different failure mechanism (surface morphology) involved and also the justification for the wear models is required from this study.

## 1 Materials, Processing and Testing of Composites

### 1.1 Materials

The materials such as long jute fibers, long sisal fibers, epoxy and hardener used for preparing natural composite are presented in Table 1. The reason for selecting the long jute and sisal fibers is updated in the general introduction. The surface energy, slenderness ratio and also the curing time is most important for the effective development of adhesion strength between fiber surface and the resin. The long fibers have the larger surface area of interaction with the resin which could develop the good surface energy. The weight fraction percentages are selected based rule of fiber-matrix volume fraction. According to the rule of mixture, the weight percentage of the reinforcement in composites made of epoxy 30% with ±3% acceptable limit. Also, in special cases, the implementation of a minimum weight fraction of 5% for each fiber will prevent fiber overlap. This is the study on long natural fibers and it could provide the foundation for a future rise in the accounted weight fraction. The material used for preparing of composite is presented in Table 2. The designed material system for preparing of composite is also recorded.

**Table 1 Materials used for fabrication with size and density properties**

| Materials | Designation | Form and size | Density (kg/mm$^3$) |
|---|---|---|---|
| Epoxy LY556 | EP | Liquid | 1.13 |
| Hardener (HY951) | H | Liquid | - |
| Sisal fiber | SF | 15 to 30 mm | 1.35 |
| Jute fiber | JF | 15 to 25 mm | 1.54 |

**Table 2 Materials used for the processing of composites**

| Materials | Designation | Fiber and matrix (wt. %) | |
|---|---|---|---|
| | | SF/JF | Epoxy |
| Epoxy | EP | -- | 100 |
| 4 wt.% sisal/ 4 wt.% jute /Epoxy | NFPC-08 | 8 | 92 |
| 8 wt.% sisal/8 wt.% jute/ Epoxy | NFPC-16 | 16 | 84 |
| 12 wt.% sisal /12 wt.% jute/ Epoxy | NFPC-24 | 24 | 76 |
| 16 wt.% sisal /16 wt.% jute/ Epoxy | NFPC-32 | 32 | 68 |

## 1.2 Fabrication of Epoxy Composites

The designed composite plate has been casted using hand lay-up technique through the wooden mold of dimension 120 mm×100 mm×6 mm. The composite plates were prepared as per the formulations of composite system in which the weight fraction percentage of fibers varying from 8, 16, 24 and 32 with equal proportions of jute and sisal fibers.

The composites were processed using epoxy LY556 combined with hardener HY951. The typical manual lay-up procedure was used to prepare the samples. A glass jar containing a defined volume of epoxy resin and hardener (10 : 1 by weight) was placed in a vacuum chamber to eliminate air bubbles caused by the different volume fraction of fibers. To make removing the mold plate easier, the glass plate was covered with the mold release sheet. Additionally, the interior surface of the mold was coated with the mold release spray. A thin layer of the liquid (2 mm thick) was poured after setting the mold on a glass sheet. The surface was covered with the necessary weight fraction percentage of fibers. The curing of samples was done with the application of compressive load for 72 h. Fig.1 depicts the stages involved in the manufacturing of a laminated composite created by hand lay-up method. The specimens were prepared with a thickness of 6 mm. Further, according to ASTM standards, samples for mechanical and wear tests were prepared by cutting using metallographic diamond cutting machines.

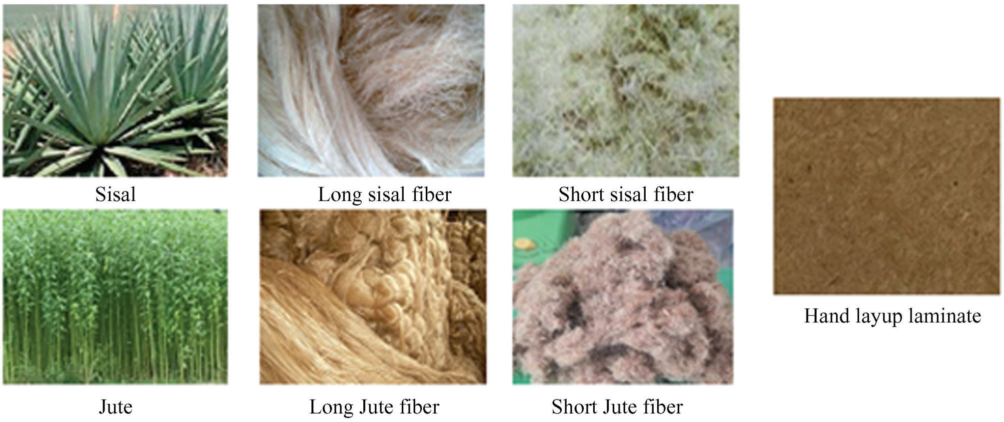
Sisal
Long sisal fiber
Short sisal fiber
Jute
Long Jute fiber
Short Jute fiber
Hand layup laminate

**Fig.1 Natural fiber processing steps and hand lay-up laminate of composites**

### 1.3 Testing of Natural Fiber Composites

The natural composite samples were prepared according to ASTM D 3039-08, ASTM D790-02 and ASTM E10-14 standards for tensile strength, flexural strength and Brinell hardness tests respectively (as shown in Fig.2). The uniaxial tension test and flexural tests were conducted on 5 kN capacity universal testing machine (UTM). Strain rate employed during test was about 1 mm/min. Five samples of each composition were tested and average value was considered for the present investigation. Similarly, Brinell hardness tests were conducted on each sample for five times and an average value was considered.

**Fig. 2 Tensile and flexural test samples**

The wear characteristics of the test samples was studied as per ASTM-G99 technique using pin on disc wear testing method. The square wear test samples of each side 10 mm were fastened to steel pin holder that is 8 mm in diameter and 27 mm in length using the proper adhesive glue for supporting the composite samples. Initially, the samples were then rubbed using 600 grit silicon carbide emery paper and confirm the appropriate surface interaction during constant sliding against the counter steel disc. The initial sample mass was evaluated with the aid of precision electronic mass balance of accuracy of 0.001 g. Prior to experimentation, counter disc surface must be cleansed with acetone solution to guarantee that polymer film does not exist on counter surface. Through a pivoting loading lever, a standard load has been delivered to a pin. The EN31 alloy steel disc size of 165 mm diameter, 8 mm thickness with superior hardness of 62 HRC was used during the wear test. The experimental setup of wear testing machine is shown in Fig. 3.

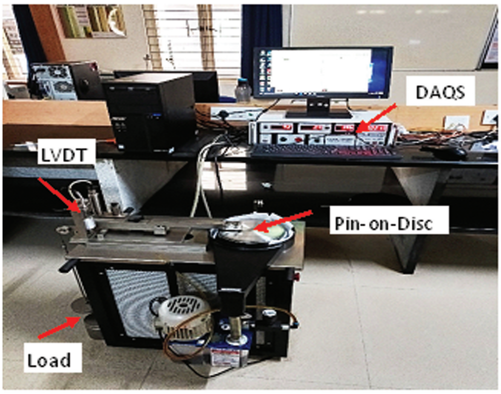

**Fig.3 Experimental set up used for sliding wear system: Pin on disc machine and specimen dimensions**

By adjusting the steel disc's duration and speed, the variables considered for the test, such as traveling distance, normal weight, and sliding velocity, were entered. When the predetermined time has passed, the machine shuts down automatically using the timer mechanism it has built in. Pin and the tested sample's final weight were both measured. The test was conducted using several experimental conditions. In every case, the samples' initial weight and final weight are determined before and after the experiment, respectively. The weight loss is measured and recorded. Three samples are tested, and the representation is based on the average statistics. The sample's weight loss ($W$) was used to calculate the sliding wear loss, and the wear volume was calculated using experimentally measured density and Ks was measured using wear loss. Eqs.(1) and (2) are used to determine the samples' wear volume and specific wear rate, respectively.

$$\text{Wear volume} = V = \frac{W}{\rho}\ \text{mm}^3 \qquad (1)$$

$$\text{Specific wear rate} = \text{Ks} = \frac{V}{F \times D}\ \text{mm}^3/(\text{N}\cdot\text{m}) \qquad (2)$$

where, $W$ represents the difference of initial weight and final weight in kg; $\rho$ is density in kg/mm$^3$; $F$ is the applied normal load in N; $D$ is the sliding distance in mm.

## 2 Results and Discussion

### 2.1 Mechanical Properties

The mechanical properties of prepared composites specimens were studied through evaluating their ultimate tensile strength, flexural strength and hardness. The variation of studied mechanical properties such as tensile strength, flexural strength and hardness for change in the percentage of different reinforcements are presented in Fig.4, Fig.5 and Fig.6 respectively. The neat epoxy illustrated the minimum mechanical properties and properties found to be improved with the increase of reinforcement percentage. Thus, it can be inferred that reinforcements play a major role in the enhancement of composite strength and properties can be further enhanced with an increase in the percentage of reinforcements such as sisal and jute. The neat epoxy possesses lower strength, and occurrence of voids and other imperfections in the prepared samples is relatively higher. Whereas, reinforcement of natural fibers to epoxy imparts the strength to resultant material. In addition, aids to reduce the occurrence of imperfections, thereby reducing the crack initiation and propagation. Perhaps, the enhanced mechanical properties of higher fiber concentration composites due to the arrest of crack propagation at low strain values. In addition, superior bonding characteristics has aided in enhancing the mechanical properties of studied mechanical composites and hybridization has probably improved stress distribution among reinforcements[4]. Thus, greater resistance is offered by the higher fiber concentration composites against load applied.

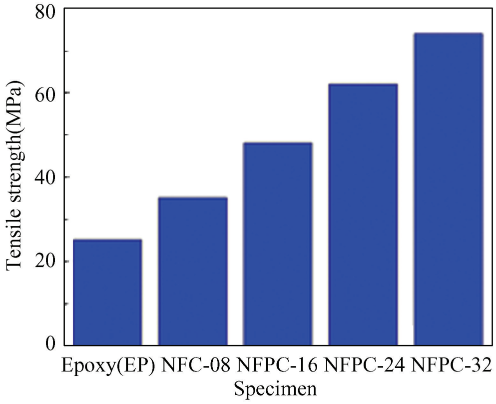

**Fig.4 Tensile strength of different composite specimens**

## 2.2 Effect of Sliding Load on the Sliding Wear Volume Loss and Specific Wear Rate

A long jute-sisal/epoxy FRCs ‘Ks’ and wear volume loss (WVL) and as a function of sliding load (SL) is depicted in Figs. 7 (a) and (b). The wear characteristics are studied by varying the load from 25 to 100 N through 25 N under the effect of constant 500 mm/s sliding velocity for a 30000 mm sliding distance. The finding of the test shows that wear loss is in a linear relationship between composition, sliding load and the interaction time.

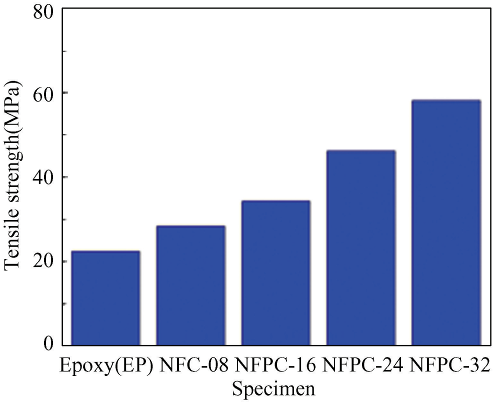

**Fig.5 Flexural strength of different composite specimens**

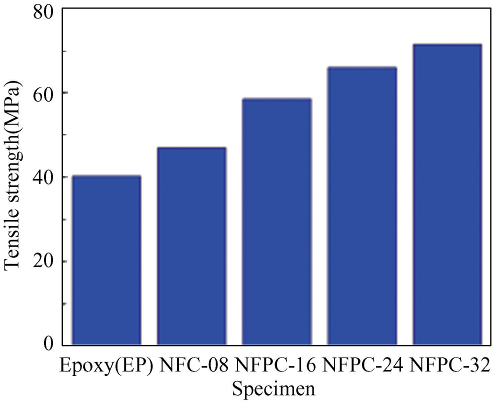

**Fig. 6 Brinell Hardness Number of different composite specimens**

The wear performance of epoxy composite under the effect of varied load and loading of fiber is shown in Fig.7(a). It can be seen that wear loss is increased when sliding load is increased. The influence of loading the fiber has diminished wear loss. Results exhibited the wear characteristic of composite which depends on sliding load, loading of fiber and the interaction time[26]. The wear loss of pure epoxy varied from 5.9 $mm^3$ to 27 $mm^3$ under the sliding pressure range examined. The wear loss increases when sliding pressure is increased. It has the largest wear loss of 27 $mm^3$ at increased sliding pressure, representing a nearly 350% increase. Due to the decreased interfacial temperature, the deformation of epoxy was smaller at lesser sliding pressure. Similar results was reported by Rajawat et al.[27] during the wear behavior study on epoxy matrix and natural fiber reinforced epoxy composites. They observed that the incorporation of basalt fiber has been improved the tribological properties of epoxy matrix under the higher load and sliding speed conditions.

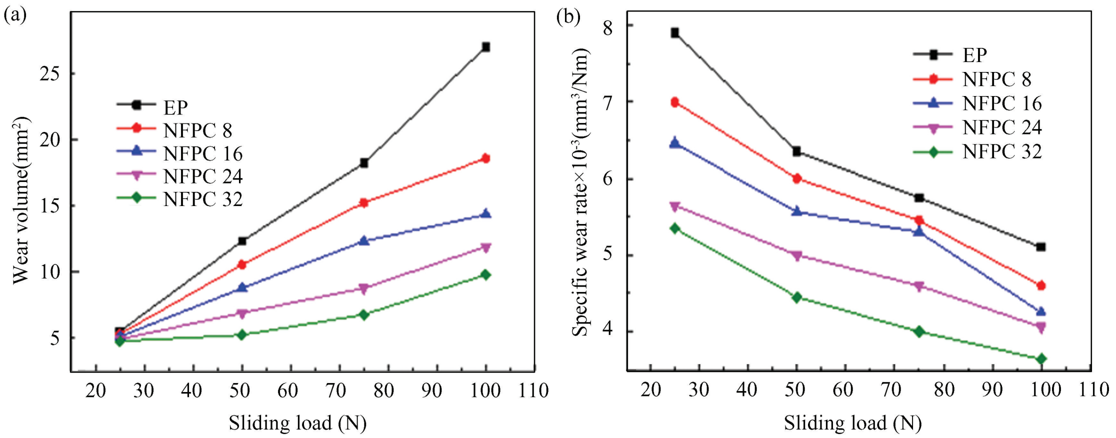

**Fig.7 Influence of sliding load on (a) wear volume and (b) specific wear rate at constant 500 mm/s sliding velocity and 30000 mm sliding distance for the FPCs**

The wear loss was the result of the deformation of matrix phase. The sliding pressure was insufficient to separate the hybrid fibers. This is owing to the significant interfacial bonding that has established between composite components. Epoxy is a crystalline polymer that can be exposed to the interfacial temperature because of friction. As a result, a rough polymer layer was produced on steel disc. This could reduce the wear loss of neat EP. The wear mechanics was entirely directed by the polymer transfer layer generated on steel surface under this situation[17, 28]. However, when the pressure rises, the frictional temperature rises, potentially leading to severe plastic deformation. The deformed surface subjected to higher pressure suffers from substantial wear loss due to surface roughness. When exposed to increasing pressure, the transfer layer created on the hardened steel surface would shatter, permitting the polymer surface to make interaction with metal, resulting in increased wear volume loss[29-30]. To withstand wear loss, the polymer substrate created by clean epoxy on the opposite surface functions as a lubricant [19, 31]. Furthermore, epoxy may be readily dragged out from an additional transfer layer, resulting in a constant, uniform, and optimum transfer layer on the steel face. This steel-formed polymer substrate links the polymer surface to the polymer layer[16, 32-33]. The surface friction was low, and the interfacial temperature was modest. This may decrease wear loss. The substantial frictional shear force fractures the transfer layer when sliding load is increased. High frictional force generates severe plastic deformation because of the weakening state of the polymer, resulting in melting wear in this case. As a result, melting wear contributes to the overall wear response of composites. At increased pressure, the distorted neat epoxy was forced to flow over the disc surface, interrupted by fragmented debris, resulting in the disc surface being transformed into a high abrasive surface. This may result in significant penetration of the soft polymer layer in order to extract a greater amount of material. As a result, increased sliding pressure results in higher wear volume loss. The epoxy has suffered the most wear volume loss of all.

Identical results were seen for EP-based composites. The wear loss of NFPC-8, NFPC-16, NFPC-24 and NFPC-32 composites have followed the similar trends as of neat epoxy. The wear loss of these FRCs enhanced as the sliding pressure increases. The wear loss of 5.2 to 19.84 mm$^3$, 4.5 to 16.58 mm$^3$, 4.25 to 14.25 mm$^3$ and 3.25 to 12.25 mm$^3$ has been encountered by NFPC-8, NFPC-16, NFPC-24 and NFPC-32 composites respectively across the studied varying sliding pressure. As compared to plain EP, NFPC-8 composite shows the less wear loss at lower pressure. It is due to matrix epoxy and hybrid fibers strong interfacial adhesion. When sisal fiber is saturated with polymer resin, it basically becomes a high strength fiber. Jute fiber acts as a support for the composites by interacting with nearby fiber and matrix. The natural fiber surface is generally rough. The fibers and matrix working together have resisted pressure application under lower pressure. Because of the matrix's and fibers' excellent compatibility, the matrix showed the least amount of distortion. But due to insufficient temperature conditions, the applied load is insufficient to remove the fiber from the matrix[28, 32]. However, under larger loads, the COF was considerable, and matrix experienced significant deformation. The composites reached the softening point because of the interfacial temperature and submitted to the imposed load. When compared to fiber wear, matrix wear has been completely taken into consideration in this case. However, because of the rough character of the fiber debris, the transfer coating that generated on the steel surface was slightly rough[8-9]. The polymer layer was removed under maximum pressure, permitting the polymer surface of fiber to interface with the rough metallic surface and cause significant wear volume loss. Similar results were seen with composites NFPC-8, NFPC-16, NFPC-24 and NFPC-32. The wear loss of EP composites has lowered due to increase in fiber loading. However, a greater proportion of fiber loading causes the non-resin zone to emerge, which is one of the main factors in the development of stress concentration at the interface. This could compromise the fiber′s structural integrity when the matrix phase is present.

Amongst all EP-based composites, NFPC-32 has demonstrated greatest wear resistance. The wear loss reduces with increasing fiber loading. Because of the composite materials strength, the harm caused to fibers was lessened at lower pressure. Fundamentally, natural fibers are brittle by nature. Jute and sisal fibers were treated to the hand lay-up process, which increased the fibers strength effectively sizing them with polymer resins[9]. Large portions of the fibers' surface area were subjected to the sliding load under the low pressure condition. As a result, there may be reduced wear volume loss due to fiber surface sliding instead of the matrix. Higher pressure caused the broken fibers that were encased within the matrix to become exposed to the sliding surface. Because of the abrasive characteristic of natural fibers, the transfer layer that was created as result of intense sliding become rough and abrasive[11]. The abrasive transfer film was made to interact with the broken fibers that were placed on the polymer surface, causing an interaction across abrasive surfaces. By doing this, the polymer surface might not be severely worn. Because polymers contain rigid fibers, the development of frictional temperature at the contact between surfaces is reduced. This has prevented the early reaching of polymer′s softening point. Hence, less wear loss. The formed transfer layer on the steel counter surface which was the result of dragging the polymer resin was strengthened by the hard broken fibers. The large volume loss was the result of both fiber wear and matrix wear. When sisal fibers are exposed to higher pressure, fiber crushing occurs, which results in embedding of these crushed fibers strongly in the polymer layer on the disc. Perhaps, overriding of the polymer surface against the hard steel surface is prevented. This may controls the wear loss. The behavior of composites agrees well with the previous research [9, 13-15].

Fig.3(b) illustrates how fiber loading and sliding pressure affect the Ks of composites. The graph demonstrates that when sliding pressure increases, " Ks" decreases. Additionally, it was discovered that Ks of composite decreases due to fiber composition. The " Ks" of pure epoxy varied throughout the range of sliding pressure examined, ranging from $7.9\times10^{-3}$ to $5\times10^{-3}$ $\mathrm{mm}^3/(\mathrm{N}\cdot\mathrm{m})$. Similarly, $6.9\times10^{-3}$ to $4.58\times10^{-3}$ $\mathrm{mm}^3/(\mathrm{N}\cdot\mathrm{m})$, $6.45\times10^{-3}$ to $4.32\times10^{-3}\mathrm{mm}^3/(\mathrm{N}\cdot\mathrm{m})$, $5.7\times10^{-3}$ to $3.98\times10^{-3}$ $\mathrm{mm}^3/(\mathrm{N}\cdot\mathrm{m})$ and $5.3\times10^{-3}$ to $3.5\times10^{-3}$ $\mathrm{mm}^3/(\mathrm{N}\cdot\mathrm{m})$ specific wear rate exhibited by NFPC-8, NFPC-16, NFPC-24 and NFPC-32 composites respectively. The transfer layer that was created on the steel disc was an outcome of fiber crushing which caused the wear rate to decrease. Furthermore, the wear volume of the composites has been regulated by the adhesive strength between natural fiber and resin, namely high strength jute fiber. Due to this, composites are wearing down more slowly. Among the composites examined, NFPC-32 composites have had the lowest rate of wear. The impact of jute fibers is more dominant over sisal fibers due to their structural stability. Perhaps, improved mechanical properties due to hybridization of reinforcement owing to the enhanced interfacial bonding[32-33]. The moisture absorption of sisal fibers is the major draw-back when they were put for combined effect during the fabrication process. Further, the non-resin zones were also contributed for the wear loss.

### 2.3 Effect of Sliding Velocity on the Wear Volume loss and Specific Wear Rate

The sliding wear behavior of EP, NFPC-8, NFPC-16, NFPC-24 and NFPC-32 composites under the impact of different sliding velocities is presented in Figs. 8 (a) and (b). The experimental range of velocity considered for the test was 500 to 2000 mm/s for a particular sliding load of 25 N through 30000 mm sliding distance. The experimentation showed that the wear loss increases with an increase in the speed of the steel disc. The wear loss of neat EP was more when compared to NFPC-8, NFPC-16, NFPC-24 and NFPC-32 fibrous composites. Under lower velocity, the volumetric loss of neat EP was 2.1 mm$^3$. The wear response of composites is a linear function of velocity. The wear response of 14.25 mm$^3$ was exhibited by EP at a higher velocity which is 85. 26% increase. For increase of 300% sliding velocity, 85.26% increase in volumetric loss was showed by neat EP. But the addition of 8 wt. % of sisal and jute fibers (4 wt. % each) into EP decreased the wear volume loss of NFPC-8 composites. It is 11.10% and 4% reduction in wear response of NFPC-8 composites over neat EP was noticed between the ranges of experimental velocity respectively. Same trend was noticed with NFPC-16 composites. It is 28. 5% at lower velocity and 24% at peak velocity has been recorded over neat EP. But the hybrid effect of NFPC-24 and NFPC-32 composites have effectively reduced the wear volume loss over neat EP. It was 2.14 mm$^3$ and 2. 49 mm$^3$ respectively at lower ad higher sliding velocity which is very less compared to neat PP at the respective sliding velocities[34]. Therefore, it is found that higher sliding speed of natural fibers significantly improved sliding wear resistance of NFPC-8, NFPC-16, NFPC-24 and NFPC-32 fibrous composites.

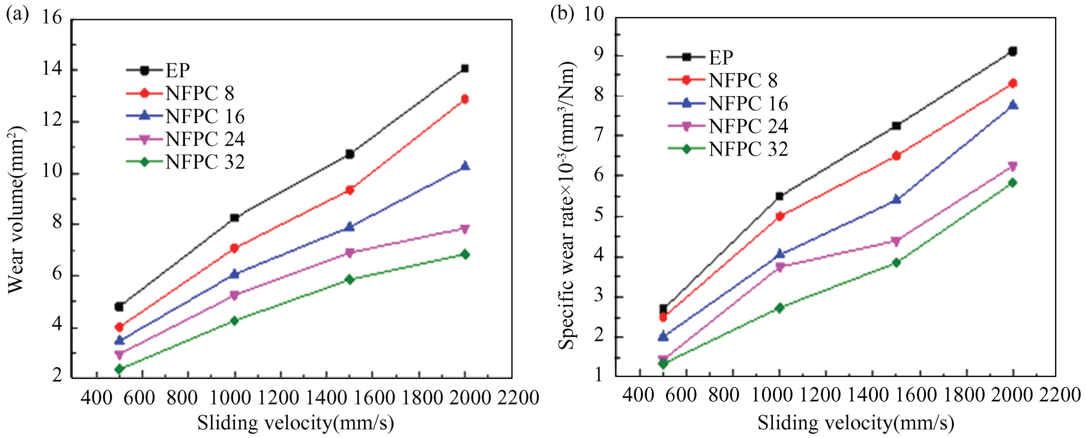

**Fig. 8 Influence of sliding velocity on (a) wear volume and (b) specific wear rate at constant 25 N sliding load and 30000 mm sliding distance for the FPCs**

At lower speed, the frictional force generated at the interfacial surface was less. But the frictional force at the surface increases with increase in sliding velocity. The frictional asperities which were generated from both broken fibers of sisal, jute, and EP interacting at the contacting surfaces generate high temperature[35]. NFPC-8 composites exhibit better wear volume loss compared to neat EP. At lower sliding velocity, the frictional force at the surface was prevented by plastic deformation of neat EP. The transferred semi crystalline substrate of polymer EP on to the steel prevented the wear of NFPC-8 composites. Higher the speed, higher would be the interfacial temperature. When the temperature at the interface reached the softening point of a polymer, the adhesive component from the polymer surface transferred easily on to the metallic surface resulting in the formation of transfer layer [36]. The transfer layer occurrence has offered resistance against direct contact between disc and composites surface. Thereby, wear loss was reduced. In addition, jute fiber supported a part of applied load against the frictional force. Similarly, sisal fiber is thermally strong and avoids the melting wear of matrix. It avoids the early reaching of softening point of polymer. Therefore, less wear volume loss.

The effect of fiber reinforcement under varying sliding velocity on ‘Ks’ of NFPC-8, NFPC-16, NFPC-24 and NFPC-32 fibrous composites are depicted in Fig. 8(b). It has been observed that ‘Ks’ depends on sliding velocity for all composites tested[31]. It is found that ‘Ks’ increases with increase in sliding velocity. The Ks of neat EP was found to be high when compared to all other composites tested. The specific wear rate of EP was varied from $2.59\times10^{-3}$ to $8.5\times10^{-3}$ $mm^3/(N\cdot m)$. Similarly, the specific wear rate of NFPC-8, NFPC-16, NFPC-24 composites ranges varies from lower of $1.4\times10^{-3}$ $mm^3/(N\cdot m)$ to $2.41\times10^{-3}$ $mm^3/(N\cdot m)$ and higher of $6.1\times10^{-3}$ $mm^3/(N\cdot m)$ to $8.04\times10^{-3}$ $mm^3/(N\cdot m)$ respectively. But the specific wear rate of hybrid fiber filled NFPC-32 composite varied from $1.18\times10^{-3}$ $mm^3/(N\cdot m)$ to $5.59\times10^{-3}$ $mm^3/(N\cdot m)$ which is 54.4% and 34.23% less than the wear rate of neat EP between varying velocities. This may be due to high shearing force which sheared the transfer layer on the counter polymer surface than frictional force at higher velocity[37]. Among all the composites, NFPC-32 composites showed excellent wear rate. The present findings are in line with the results of others work[33]. Composites studied are in order of NFPC-32 > NFPC-24 > NFPC-16 > NFPC-8 in exhibiting the wear resistance under the impact of sliding speed.

The scanning electron microscope (SEM) pictures of worn surface of natural composites under the influence of sliding pressure are shown in Figs. 9 (a) and (b). Fig. 9(a) shows the SEM pictures of the wear out surface under the effect of lower pressure. The figure shows that plastic deformation of neat epoxy has resulted in a moderate amount of melting wear. Further, the crystalline nature of these resin will experiences small melting patches. The neat uniform worn surface with reduced number of scratches is observed. The light wear tracks that slide across the surface are the result of micro deformation. In contrast to fiber wear, matrix wear is visible on surface[25]. Less wear loss has been exhibited as a result of excellent transfer layer on the disc. Fig.9(b) shows a SEM of the neat epoxy composites′ worn surface under the result of increased sliding pressure. Here, the melting wear is more pronounced. The surface patches are seen as a result of matrix melting wear. Furthermore, because of tidy epoxy's crystalline composition, little zig-zag wear tracks are visible. On the surface, there are visible zig-zag patterns. These are the outcomes of the epoxy's stacking structure during processing. The rough surface can be witnessed in the figure as an outcome of severe deformation brought on by a strong frictional force at the interface. The SEM of NFPC-8 composites' worn surface is shown in Figs. 9 (c) and (d). Fig. 9(c) shows the NFPC-8 composites' worn surface as a result of lower pressure. The matrix's modest distortion is depicted in the figure. Because there is less frictional force at the surface, bright patches are visible there. Wear debris has accumulated ad are visible on the surface[30, 39-40].

The effective engagement of the fiber at the interface is also apparent in the pulverizing of fiber debris. Similar findings are supported by the worn surface of NFPC-8 composites when subjected to increased pressure (Fig. 9(d)). On the surface, melting of matrix and crushing of fibers can be seen. The rubbing motion of the surface with the steel disc has revealed the abrasive character of the worn surface despite its uneven wear. Also, the matrix wear debris is visible on the surface as a result of sliding pressure. However, the fibers separate and appear to be relatively sparse even at increased pressure. Thus, wear loss has occurred due to the mechanism of fiber breakage and fiber pull out due to the penetration of asperities from the counterface during sliding phenomenon.

Figs. 10 (a) and (b) depict the failure surface of NFPC-32 composite as a result of varied pressure. The influence of lower sliding pressure made the surface to be rough and moderately abrasive. The fiber detaching impressions are observed on the surfaces. Matrix deformation is small compared to others. However, it has been noted that the influence of sliding pressure in harsh conditions is highly rough and that wear debris agglomerations are not homogeneous. On the surface, melting regions are visible as a result of a greater number of fibers agglomerating [27, 31, 40]. The result of significant wear loss is severe matrix melting and fiber wear. However, the material′s resistance to wear and volume loss clearly demonstrates the effect of hybrid fibers and resin′s interaction. Even at high pressure, smaller and shallower patches are seen. This demonstrated that the transfer layer, which was created as a result of matrix deformation during the early stage of sliding movements, was enhanced by an increased fraction of fibers. As a result, NFPC-32 composites have shown improved wear resistance.

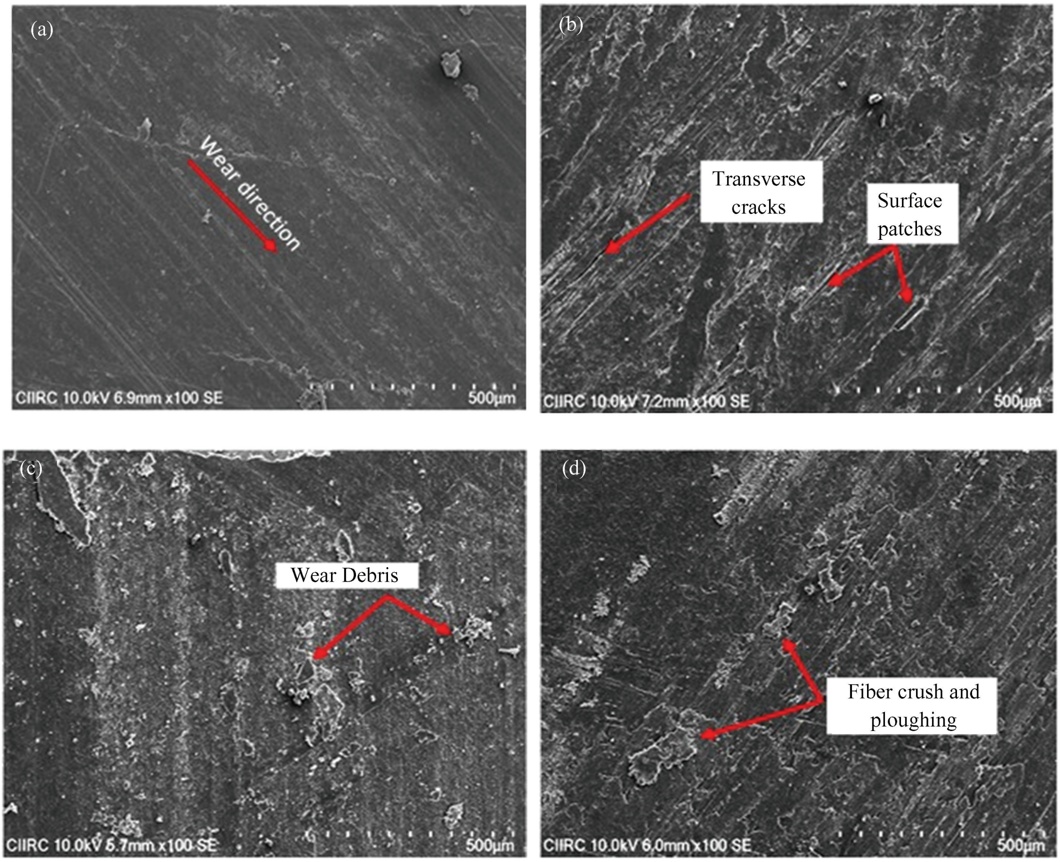

**Fig. 9 The SEM images of the worn surfaces of epoxy based composites under the influence varying pressure: (a) EP composite (25 N);(b) EP composite (100 N); (c) NFPC-8 composite (25 N) and (d)NFPC-8 composite (100 N)**

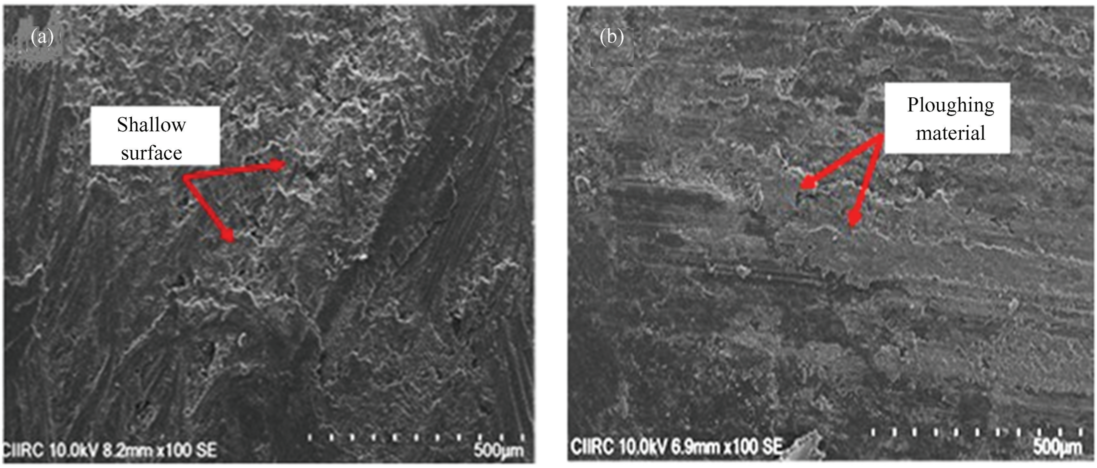

**Fig.10 The SEM images of the worn surfaces of Epoxy based composites under the influence varying pressure: (a) NFPC-32 composite (25 N) and (b) NFPC-32 composite (100 N)**

## 3 Conclusions

The following conclusions are drawn from the investigation of dry sliding wear behavior of epoxy based NFPCs:

1) The composites of EP, NFPC-8, NFPC-16, NFPC-24 and NFPC-32 were successfully fabricated using hand lay-up process.

2) The wear tests of composites were executed

using pin-on-disc machine with different sliding velocities of 500 mm/s to 2000 mm/s, sliding loads of 25 N to 100 N and sliding distance was kept constant at 30000 mm.

3) The results indicated that the wear volume increases from 3.25 to 12.25 $mm^3$ with an increase in sliding pressure. However, specific wear rate decreases from $5.3\times10^{-3}$ to $3.5\times10^{-3}$ $mm^3/(N\cdot m)$ with an increase in sliding pressure in NFPC-32 composite when compared to all the other composites.

4) Similarly, the wear volume and specific wear rate increases from 2.25 to 6.3 $mm^3$ and $1.18\times10^{-3}$ to $5.59\times10^{-3}$ $mm^3/(N\cdot m)$ respectively with increase in sliding velocities in NFPC-32 composite when compared to all the other composites.

5) The morphological study of the worn surfaces through SEM images showed that melting wear, pulverization of fibers and deformation of matrix were some of the abrasion mechanisms observed for the failure of composites.

6) The sisal fiber and the jute fiber were proved to be the best potential fiber for tribological applications.

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