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Fiber Loading Response on Wear and Friction Behavior of Polypropylene Natural Hybrid Composites

[1]Mahesha A, [2]Rudresh B M, [3]Reddappa H N, [4]Madhu D

[1]Assisatnt Professor, [2]Assistant Professor, [3]Associate Professor, [4]Professor
[1]Department of Mechanical Engineering
[1]Government Engineering College, Ramanagaram -562159, Karnataka, India

Abstract: The effect of fiber loading on wear and friction behavior of Ramie fiber and Sisal fiber reinforced Polypropylene composites was studied. The impact of sliding pressure and sliding velocity on the wear rate and frictional behavior was investigated. Four material systems were selected for the investigation: Neat Polypropylene (PP), 5 wt. % of Ramie fiber (RF) and Sisal fiber (SF) each (PP/10), 10 wt. % RF and SF (PP/20) and 15 wt. % RF and SF (PP/30). These composites were developed using twin screw extrusion method through melt mix followed by injection molding. The sliding wear behavior of these composites was investigated using ASTM G99 method by varying sliding pressure (25, 50, 75 and 100 N) under the action of sliding velocity 0.5 m/s for a sliding distance of 4000 m. The equal contribution of fiber loading was studied and the experimented results were presented. The results showed that wear volume loss of composites decreases by the reinforcing effect of hybrid fibers. The frictional coefficient decreases with increase in fiber loading. Further, it was observed that the tribological response is a function of sliding pressure and velocity. The wear rate decreases with increase in sliding pressure. The wear response is very much sensitive to sliding velocity rather than sliding pressure. The worn surfaces were studied using SEM images. It was revealed that the critical wear volume loss is due to both matrix wear and fiber wear. Among the composites studied, PP/30 exhibits the better wear resistance.

***Index Terms* – Polypropylene, Ramie fiber, Sisal fiber, hybrid fibers, sliding wear, friction**

I. INTRODUCTION

The effect of sliding pressure and friction are the major cause for the wear of mechanical components which are made of engineering materials. The structural materials may be metal, ceramic or polymer. But in most of the situations, polymer materials are preferred because of their self lubrication, light weight and high specific strength and modulus (M.E. Vallejos et al, 2012). The thermoplastic materials are best suited for the applications because of their anti- wear properties. It is well documented in the literature that the mechanical structures are failing during their performance because of simultaneous stress and tribological response. It is not possible to sustain both mechanical and tribological loading by the homopolymer. Therefore, polymer modification is required for the effective development of polymer composites. Polymer blending, copolymerization and reinforcing polymer by fibers and or fillers are the different methods of modification. Some of the potential fibers such as glass, carbon, Kevlar, Basalt fibers have proved their potentiality in the field of structural applications to improve both mechanical and tribological behavior. But the usage of natural fibers seemed to be the best fillers for the environmental and weight/ strength issues are concerned (Sulawan Kaewkuk et al., 2013). Sisal fiber, jute fiber, Banana fiber, coconut shell fibers etc., were already in use for the development of natural composites using thermoset resins like epoxy, polystyrene etc., But the processing of these natural fibers with thermoplastic is challenging job because of lesser density and high thermal conditions. Most of the thermoplastics such as Polyamide66, Polypropylene (PP), Polyoxymethylene (POM), PPS, PTFE etc., are the effective matrix materials used for the development of thermoplastic polymer composites (Denis Mihaela Panaitescu et al., 2015). Many researchers have contributed their work to the field of tribology of natural composites.

The reinforcement effect of sisal fibers on the dry sliding wear behavior of coconut sheath fiber reinforced Polyester composites was reported (Muthukumar Chandrasekar et al., 2021). They developed these composites using hand lay up technique. They studied the effect of sliding load and velocity on the dry sliding wear behavior as per ASTM G99. The results showed that the hybrid effect of fibers exhibits the better wear resistance compared to individual fibers. Further, they showed that deep penetration of matrix and rough surface of natural fiber reinforced composites were some of the reason for the high wear volume loss.

The effect of surface treatment of Coccinia India (CI) fiber reinforced polymer composites and their wear behavior has been reported (Bhuvaneshwaran Mylsamy et al., 2020).They selected two sizing agents such as 5 wt. % sodium hydroxide and 3 wt. % silane. They used hand lay-up and open mould technique to develop the composites. The fiber of 35 wt. % with a length of 30 mm was used for the production. The test was carried out with varying loads from 15 through 30 N insteps of 5 N, and a sliding speed (1.413, 1.884 and 2.356 m/s) through 15 minutes dry run condition. It was observed from the experimented results that the weight loss of composites treated with NaoH and silane were reduced by 15% and 39% respectively, while the coefficient of friction has been decreased by 41% and 39% respectively. The effect of hybridization of fibers on the sliding wear behavior of fiber reinforced epoxy composite was investigated (Meenakshi and Krishnamoorthy, 2020). They processed composite in the form of laminates using flax fiber, sisal fiber and glass fibers. They studied the effect of both treated and untreated fibers on the wear response. They used vacuum assisted resin transfer molding method. They studied the wear behavior by varying sliding velocity with a constant load of 10 N. It was observed that the composite with more natural fiber has approximately 20%–40% lesser wear rate and weight loss comparatively to glass and flax fiber. Hence, the potential of natural fibers in polymer composites for structural application is greatly appreciated. Exploring the hybrid effect of banana and jute fiber on the mechanical and wear behavior of epoxy based polymer composites has been carried out recently (Suresh et al., 2021). They used untreated both banana and jute fiber with epoxy resin-LY556 with HY951 as hardener. The dry sliding wear test has been conducted as per ASTM G99 by varying the sliding velocity and load. The triboogical response of the material was greatly influenced by the composition of fibers and their percentage. It was observed that the effect of sliding load was overmuch sensitive to wear behavior than sliding velocity. Further, the wear volume loss has been declined due to hybrid effect of natural fibers. The synergistic effect of bidirectional silk fiber and nano clay on the friction and wear behavior of High Density Polyethylene (HDPE) based polymer composites have been presented (Wani et al., 2018). They developed the composites for the weight fraction percentage of clay of 0.5 and 1 %. They selected the load of 10, 20 and 30 N for varying sliding distance. They showed that the wear volume loss increases with increase in sliding distance. The coefficient of friction was varying from 0.12 to 0.37 for all the sliding distance studied. 1 wt. % of clay in composites exhibited the best sliding wear resistance compared to all other composites. The effect of surface treatment of areca sheath fibers on the sliding wear behavior of epoxy composites has been studied and reported by Shaksi shantharam et al [9]. The surface treatment of fibers was carried out using 1% alkali, 0.5% KMnO4, 4% $(C6H5CO)_2O_2$ and 1% $C_{17}H_{35}COOH$. Sliding wear behavior has been carried out under the influence of sliding speed of 1.88, 3.77 and 5.65 m/s through 10, 20 and 30 N sliding load. It was observed from the experimented results that the least wear rate has been exhibited by the fibers which were treated with 1% $C_{17}H_{35}COOH$. Further, the wear rate of composites has been increased with increase in sliding speed and load.

The synergistic effect of short human hair fibers and solid glass sphere on the sliding wear behavior of epoxy composites was studied (Bishnu Prasad N and Alok Satapathy, 2018). They considered 2, 4 6 and 8 wt. % of hybrid fibers in epoxy composites along with 10 wt. % of micro spheres of glass and reported their effect on flexural and tensile strength. Further, they studied the sliding wear behavior of these composites under the influence of different experimental parameters as per ASTM G99. They used the concept of design of experiment in order to study the significant controlling factors on the dry sliding wear behavior of epoxy composites. Both mechanical wear experimentation results revealed that the hybrid effect of both the solid fillers and fibers significantly improved the mechanical strength and wear resistance. The effect of walnut content on the mechanical and sliding wear behavior of Ramie - Glass reinforced epoxy hybrid composite shave been investigated (Ravi Gupta et al, 2021]. They developed the composites by varying the walnut content from 0 to 9 wt. % in steps of 3 wt. % keeping the fiber composition at 5 wt. %. The results showed that the inclusion of walnut effectively enhanced the mechanical strength of the composites. Further, the hardness of the same has been improved due to the addition of these walnuts. The Taguchi experimentation revealed that the sliding velocity and the walnut composition have played the most significant controlling role in defining the wear behavior of hybrid epoxy composites. The hybrid effect of Himalayan Nettle/Bauhinia-vahlii fibers on sliding wear behavior of fiber reinforced epoxy composites has been reported (Sandeep Kumar et al., 2020). They studied the void fraction and water absorption capacity of these fiber reinforced composites by varying the fiber percentage from 2 to 6 wt. %. On the other hand, the mechanical behavior in terms of tensile strength, flexural strength and impact strength along with the hardness was studied and evaluated based on ASTM method. The hybrid composition of 6 wt. % enhanced tensile strength (34.04 MPa), flexural strength (42.45 MPa) and hardness of 37.01 Hv respectively. They showed that the effect of hybridization has enhanced the strength and hardness. Further, these composites were subjected to design of experiment concept to study the significant controlling factors on the wear behavior. They considered fiber composition, sliding velocity, load and distance as the process parameters for the experiment. They proved that the hybrid effect was greatly enhanced the wear resistance. Sliding velocity seemed to be the most sensitive among the process parameters considered. The synergistic effect of micro fillers on the large scale wear characterization of Hybrid Jute/ Basalt fiber reinforced vinyl ester and polyester thermoset composites have been investigated (Sukumaran et al., 2020). They used reciprocating wear testing machine for testing composites. For strengthening the transfer film on the counter surface, lubricants such as MoS_2, PTFE and POM fillers were used for the integrity of transfer film. Wear behavior of composites suggested that the PTFE filled composite exhibited the least wear resistance against highest wear resistance of MoS_2 filled ones. The thermal degradation and abrasion of the counter surface seemed to be the most failure mechanisms noticed during the investigation. The effect of adding wood charcoal particles with periwinkle shell on the tribological behavior of polyester composites has been investigated (Edoziuno et al., 2021)]. The micro composites were developed using 75 µm sized wood charcoal and periwinkle shell. These fillers were mixed in the ratio of 25:75. The hardness and dry sliding wear behavior has been examined using Brinells hardness tester and tribometer. It was found from the experimentation that the dry sliding wear behavior has been enhanced using the combination of hybrid particulates. The optimal ratio of these fillers for the effective wear resistance was developed using one factor RSM design. The tribological response of polymer composites using plant fibers were investigated (Moti Lal Rinaw et al., 2021).They optimized the tribological response of polymer composite using plant fibers. The plant fibers such as jute, flax and hemp fibers were used as the effective plant fibers to improve the tribological behavior of epoxy based polymer composites. Design of experiment showed that the frictional force, coefficient of friction and specific wear rate have discrete impact on the composition of the samples.

The reinforcement effect of carbon fiber, jute fiber and hemp fiber in the form of woven fabrics on the sliding wear behavior of epoxy composites has been investigated (Dario De et al., 2020). The developed these composite using vacuum fusion process. They studied dry sliding wear under the influence of varying sliding load. It was observed from the experimented results that the hemp fiber reinforced composites exhibited the better wear resistance under longer time and also at higher loading conditions. The tribological response of basalt fiber (BF) reinforced Polyether-Ether-Ketone (PEEK) composites have been investigated for different wear conditions (Bowen Wang et al., 2021). The surface roughness increases with increase in basalt fiber and frictional coefficient decreases attributing to the formation of transfer film on the counter surface. When the BF composition in composites was 25 wt. %, the composite exhibits the least wear rate of $5.28 \times 10^{-7} m^3/N$- m which is lower than neat PEEK. The thermal effect on the micro-tribo behavior of natural fiber reinforced Polypropylene composites has been reported (Faissal Chegdani et al., 2020). Nano indentation and scratch test were used to define the wear resistance properties of Polypropylene composites. They used flax fibers as the reinforcement agent for the development of fiber reinforced composites. Results showed a different thermomechanical property between flax fibers and PP. The stiffness of PP matrix decreases with increase in sample temperature. But the stiffness of flax fibers showed variation for change in sample temperature from 25 °C to 100 °C with a maximum at 60 °C. This is attributed to the modification of chemical composition of flax fibers due to increase in thermal effect.

From the above literature survey, it is noticed that processing of natural polymer composites using thermoplastic resin is very limited. The composites developed using natural fibers such as jute, banana, coconut sheath fiber, cotton fiber and their hybridization etc., using thermoset resins such as epoxy, polystyrene, polyester were abundant in supply. But the hybrid reinforcement effect of Ramie fiber and Sisal fiber were not reported. Further, the development of natural composites using Polypropylene based Ramie and Sisal fiber reinforced polymer composites is not reported. The adhesive wear behavior of natural fiber reinforced composites requires critical attention and investigation. Therefore, keeping this in view, an attempt has been made to investigate the effect sliding pressure on wear and friction behavior of Ramie and Sisal fiber reinforced Polypropylene hybrid composites.

II. Materials, Processing Methods and Testing of Composites

2.1 Materials used in the Development of Composites

The following sections presents the detailed study of materials used in the development of polymer hybrid composites, their processing technique and testing of polymer hybrid composites. The suppliers data used in the development of these Polypropylene based hybrid composites is detailed in the table 1. The polymer materials and natural fibers used for the development of hybrid natural composites are shown in table 1. The physical data of the materials as supplied are in the same table. The weight fraction formulation of the materials used for the production of composites is shown in the table 2.

Table 1. Data of the materials used in the fabrication process

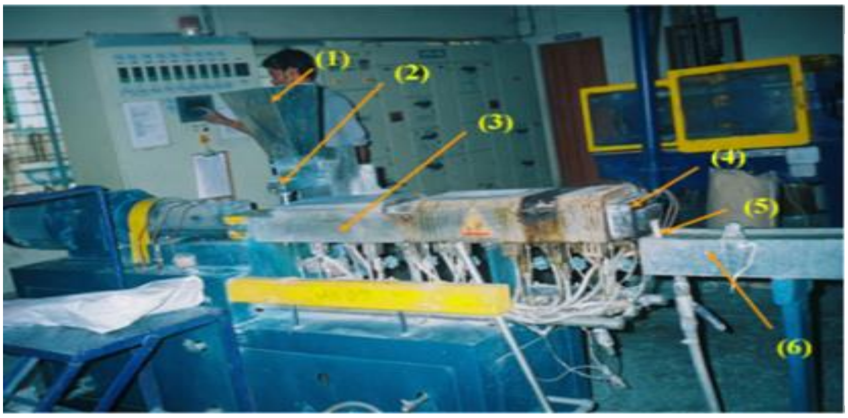
Materials	Form and size	Suppliers Details	Melting temperature	Density (gr/cc)
Polypropylene	Granules (10 to 12) (μm)	GLS Polymers, Bangalore , India	160	0.9
Maleic grafted anhydride	Powder (10 to 12 (μm)	GLS Polymers, Bangalore , India	53	1.5
Ramie fiber	5 to 10 mm	GLS Polymers, Bangalore , India	---	1.5
Sisal fiber	5 to 10 mm	GLS Polymers, Bangalore , India	----	1.5

Table 2. Formulations of material system in weight fraction percentage

Materials	Designation	Weight fraction percentage			
		PP	MagH	SF	RF
Polypropylene	PP	97	3	---	---
Polypropylene/5 wt.% sisal fiber/ 5 wt.% Ramie fiber	PP/10	87	3	5	5
Polypropylene/20 wt.% sisal fiber/ 10 wt.% Ramie fiber	PP/20	77	3	10	10
Polypropylene/15 wt.% sisal fiber/ 15 wt.% Ramie fiber	PP/30	67	3	15	15

2.2 Processing and Fabrication of Composites

The materials used for the fabrication process such as Polypropylene were dried at a temperature of 80^0C for 48 hours before mixing to avoid plasticization and hydrolyzing effects. To maintain the homogeneity of the mixture, these mixtures were mixed in the mixer. The mixture was extruded using Barbender co-rotating twin-screw extruder (Make: CMEI, Model: 16 CME, SPL, chamber size 70 cm^3) (Figure 1). The extruder consists of five heating zones where the temperature maintained in these zones were zone1 (220 ºC), zone2 (235 ºC), zone3 (240 ºC), zone4 (265 ºC) and zone5 (270 ºC) respectively and the temperature at the die was set at 220 ^{0}C. The extruder screw speed was set at 100 rpm to yield a feed rate of 5 kg/h. The extrudates obtained was in the form of cylindrical rods which were quenched in cold water and then palletized using Palletizing machine. During initial stage, around 1 to 1.5 kg of initial extrudate was removed to get the pure blend and to remove impurities of extrudate of previous stroke of the extrusion. Before injection moulding, all polymer blended pallets were dried at 100^0C in vacuum oven for 24 hours. All test specimens were injection molded from the pelletized polymer material obtained from co-rotating extruder. The temperature maintained in the two zones of the barrel were zone1 (265 ºC) and zone 2 (290 ºC) and mold temperature was maintained at 65 ^{0}C. The screw speed was set at 10 – 15 rpm followed by 700-800 bar injection pressure (Figure 2). The injection time, cooling time and ejection time maintained during injection molding were 10, 35 and 2 s, respectively. All the molded specimens as per ASTM were inspected and tested visually and those found defect were discarded from testing.



1. Hopper
2. Twin screw
3. Feeding zone
4. Die of the extruder
5. Extrudates
6. Water tank

Figure 1: Twin screw extruder (GLS Polymers Pvt. Ltd., Bangalore, India)

1. Mould
2. Injector
3. Feeding zone

Figure 2: Injection molding machine (GLS Polymers Pvt. Ltd., Bangalore, India)

2.3 Testing of Composites

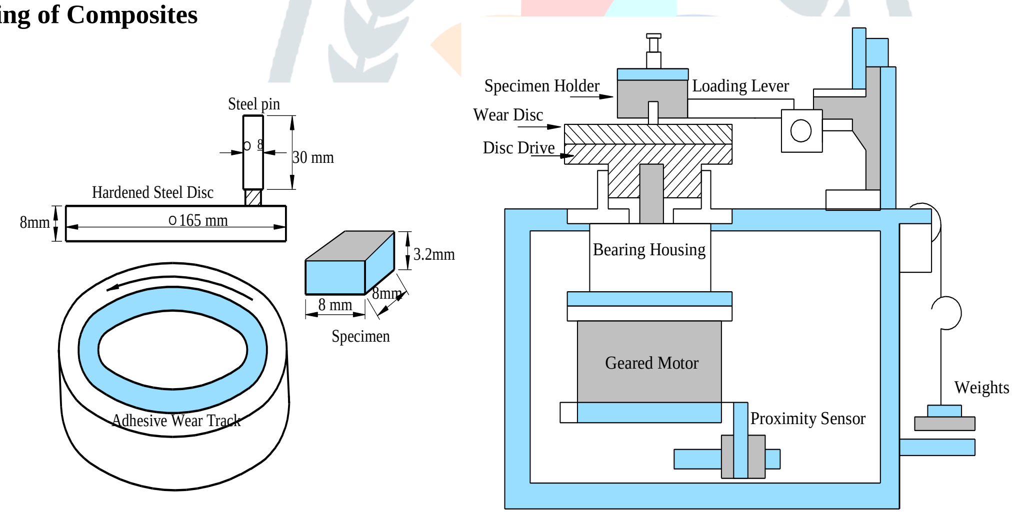


Figure 3: Experimental set up used for sliding wear system (ASTM G99): Pin on disc machine and specimen dimensions

The sliding wear behavior was evaluated as per ASTM G99 method using pin on disc machine (Fig. 3) (Ducom, Bangalore). The test samples were cut into standard dimensions (8 mm x 8 mm x 3.2 mm) and are rubbed against 600 grit SiC abrasive paper to confirm suitable polymer surface contact with counter steel disc during sliding. The test samples are glued to steel pins of diameter 8 mm and length 27 mm by using suitable adhesive. The initial weight of the specimen before test was measured using a very high precision electronic weighing balance with an accuracy of 0.0001grams (Metler Toledo). Before testing, the surface of counter disc was cleaned with acetone using a soft paper to ensure that no polymer film was present on the counter surface. A normal load was applied to a pin through a pivoted loading lever as shown in fig. 3.

The details of the experimentation have been depicted in the Table 3.The experimental parameter such as normal load, total travelling distance and velocity of sliding were inputted by setting the time and speed of the disc. When the preset time has been reached, the machine automatically stops by the timer mechanism provided in the machine. The final weight of sample along with the pin was measured. The test has been conducted for different experimental parameters. In all the cases, initial weight and weight loss after the test are measured and recorded. A minimum of three experiments were carried out to obtain the steady values and an average value is considered for the data representation.

Table 3: Experimental parameters for sliding wear test (ASTM G99)

Experimental parameters	
Sliding load (N)	75, 100, 125 and 150
Sliding distance (m)	1000

The sliding wear loss has been measured by the weight loss (W) of specimen which is then converted into wear volume using experimentally determined density (ρ). The wear volume loss 'δV' in mm^3 and specific wear rate 'Ks' in mm^3/ N-m of polymer composites were calculated using the following formulas:

$$\text{Wear volume} = \delta V = W/\rho \ \ mm^3 \quad (1)$$

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

Where ρ = density (g/cm^3), F is the applied normal load (N) and D is the sliding distance (m)

III. RESULTS AND DISCUSSION

The effect of sliding pressure on the dry sliding wear behavior of PP based natural hybrid composites were studied systematically and the response of the composite against the sliding pressure are presented in the fig. 4(a - c).

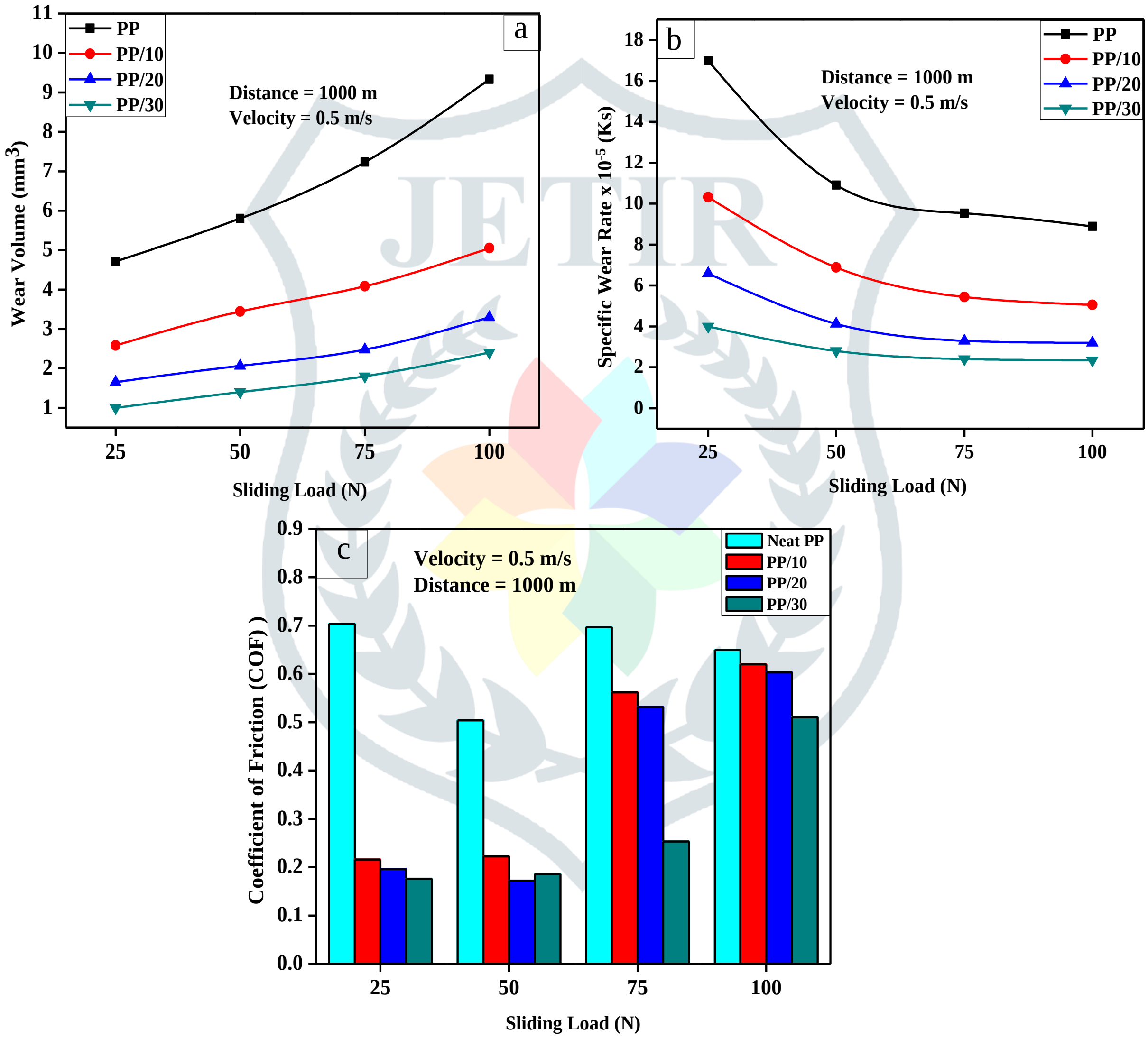


Figure 4: Tribolgical response of Polypropylene based hybrid natural composites: a) Wear volume loss, b) Specific wear rate and c) Coefficient of Friction

The experimentation was conducted at room temperature for a sliding pressure ranging from 25 N to 100 N through a sliding wear velocity of 0.5 m/s for a sliding distance of 1000 m. The test was carried out in accordance with ASTM G99 method. The response of polymer composites such as PP/10, PP/20 and PP/30 were studied and compared with the wear response of neat Polypropylene (PP). The designed material system allows equal contribution of hybrid fibers in all respect for the tribological response of natural hybrid composites. It was observed from the experimented results that the sliding wear behavior is a linear function of sliding pressure. The tribological response was documented through wear volume loss, specific wear rate and frictional coefficient. It was indicated that the wear volume loss decreases within increase in fiber loading. Further, the wear volume loss increases with increase in sliding pressure.

The effect of sliding pressure and fiber loading on the wear volume loss of PP based natural hybrid composites is shown in the fig. 4 (a). It is observed from the response curves that the wear volume loss increases with increase in sliding pressure. Also, the wear volume loss is a function of fiber loading and sliding pressure. The wear volume loss of virgin PP at lower pressure was 4.7 mm^3. As the sliding pressure increases, the wear volume loss increases. It exhibits the highest wear volume loss of 9.3 mm^3 at a higher sliding pressure which is 97.8 % increase. At lower sliding pressure, the plastic deformation of neat PP was less due to lower interfacial temperature (Faissal Chegdani et al. 2020) Further, the wear volume loss was due to matrix phase. The sliding pressure is not sufficient to detach hybrid fibers. This is due to strong interfacial bonding developed as result of compatibilizer MagH. Polypropylene is basically semi crystalline polymer which can expose itself to interfacial temperature. As a result of which, the rough polymer film was formed on the steel disc. This may impaired the wear volume loss of neat PP. But as the pressure increases, the frictional temperature at the surface increase which may lead to severe plastic deformation. Because of surface roughness, the deformed surface exposed to higher pressure leads to experience high wear volume loss. The polymer transfer film formed on the hard steel surface which was exposed to higher pressure will break allowing the polymer surface to contact with the metal leading to more wear volume loss (Dario De et al., 2020). At higher pressure, the deformed polypropylene was made to flow across the disc surface interrupted by broken debris leading to transform the disc surface to high abrasive surface. This may cause severe penetration to the soft polymer surface to remove more amount of material. Hence, high wear volume loss at higher sliding pressure. This is in good agreement with work of others (Faissal Chegdani et al. 2020, Dario De et al., 2020, Muthukumar Chandrasekar et al., 2021). The virgin PP has experienced the highest wear volume loss among all the composites studied.

The tribological response of PP/10 composites is shown in the fig. 4(a). It is observed that the wear volume loss of PP/10 composites is slightly lesser than the neat PP. PP/10 composites followed the same response of neat PP. The wear volume loss increases with increase in sliding pressure. At lower pressure, the wear response was 2.58 mm^3. But with increase in pressure, the wear volume loss of 5.05 mm^3 has been exhibited as a result of higher sliding pressure. Similarly, PP/20 and PP/30 composites followed the same trend as that of other composites. The wear volume loss of 1.64 mm^3 to 3.29 mm^3 and 1 mm^3 to 2.4 mm^3 has been experienced by PP/20 and PP/30 composites. The decrease in wear volume loss of 45%, 65% and 78.7% has been exhibited by PP/10, PP/20 and PP/30 composites at lower sliding distance. But 43.8%, 63.4% and 73.34% decrease in wear volume loss at higher sliding pressure. This showed that PP/30 composites have the highest wear resistance among the composites studied. This justifies the effect of fiber loading in improving the ware resistance of Polypropylene based natural composites (Muthukumar Chandrasekar et al., 2021,Suresh et al., 2021)

At lower pressure, PP/10 composite exhibits the least wear volume loss compared to neat PP. It can be attributed to good interfacial adhesion between matrix PP and hybrid fibers. Basically, Ramie fiber is a high strength fiber when it was wetted with the polymer resin. Sisal fiber supports the composites through its interaction with neighbor fiber and the matrix. Basically, the surface of natural composites is rough in nature. At lesser pressure, the combined effect of fibers and the matrix has resisted the applied pressure. Least deformation of the matrix has been observed due to good compatibility between fibers and matrix. But the applied load is not sufficient to drag the fibers from the matrix due to insufficient thermal conditions (Muthukumar Chandrasekar et al., 2021). But at higher load, the frictional temperature was high and severe deformation of matrix occurs. The interfacial temperature made the composites to reach to the softening point in order to surrender themselves to applied load. Here, the matrix wear has been accounted to maximum extent compared to fiber wear. But the transfer film formed on the steel surface is slightly rough due to rough nature of fiber debris (Ravi Gupta et al, 2021, Suresh et al., 2021). With maximum pressure, the polymer film was drained off allowing the polymer fiber surface to interact with the hard metallic surface leading to high wear volume loss.

Similar observations were noticed with PP/20 and PP/30 composites. As the fiber loading increases, the wear volume loss decreases. At lower pressure, the damage to fibers was less due to structural integrity of composites. Basically, the natural fibers are brittle in nature. When the Ramie fiber and sisal fibers subjected to melt mix method, the strength of the fibers would increases due to effective sizing with thermoplastic resins (Ravi Gupta et al, 2021). At this condition, large surface area of fibers was exposed to the sliding load. This may cause sliding of fibers surface instead of matrix resulting in lesser wear volume loss. The broken fibers which were embedded in the matrix were made to expose to the sliding surface as a result of higher pressure. The transfer film which was formed as a result of severe sliding becomes rough and abrasive due to abrasive nature of natural fibers (Suresh et al., 2021). The broken fibers were exposed on the polymer surface is made to interact with abrasive transfer film which made the interaction between abrasive surfaces. This may avoid the wear of polymer surface. The generation of frictional temperature at the interaction surfaces decreases due to presence of hard fibers in polymers. This has avoided the early reaching of softening point of the polymer. Hence, less wear volume loss. The behavior of composites is in good agreement with the work of others (Ravi Gupta et al, 2021, Muthukumar Chandrasekhar et al., 2021).

The effect of fiber loading and sliding pressure on the specific wear rate (Ks) is shown in fig.4 (b). It is indicated from the graph that 'Ks' of composites studied decreases with increase in sliding pressure. Also, it was observed that the wear rate of composites was purely attributed to the composition of fibers in composites. The 'Ks' of neat Polypropylene was ranging from 16.98 x 10^{-5} to 8.89 x 10^{-5} mm^3/N-m between the range of sliding pressure studied. Similarly, the specific wear rate of 10.32 x 10^{-5} to 5.05 x 10^{-5} mm^3/N-m, 6.59 x 10^{-5} to 3.2 x 10^{-5} mm^3/N-m and 4 x10^{-5} to 2.34 x 10^{-5} mm^3/N-m respectively exhibited by PP/10, PP/20and PP/30 composites respectively. The decrease of wear rate with increase in sliding pressure was due to expose of fiber surface to the sliding pressure (Suresh et al., 2021).

The rough transfer film which was formed on the surface acts as abrasive surface to rub against smooth polymer abrasive surface resulting less wear rate. The plastic deformation of the matrix was less because of the presence of hybrid fibers. Ramie fiber acts as strength holder whereas sisal fibers act as crack arrestor to improve the wear resistance of composites (Suresh et al., 2021).

The effect of sliding pressure on the coefficient of friction (COF) for the studied natural composites is shown in fig. 4(c). It is observed from the figure that COF decreases with increase in sliding pressure and fiber loading. At lower sliding pressure, the value of COF was less compared to higher value of sliding pressure. Initially, for PP, high frictional effects were observed on the surface due to semi crystalline nature of PP. But at this condition, remaining composites have exhibited very less COF. This may due to the high strength of the transfer film formed as an effect of adding deformed matrix. As the sliding pressure increases, the corresponding increase in COF has been observed (Muthukumar Chandrasekar et al., 2021). This may due to the effect of abrasive nature of the transfer film formed on the surface. The rough nature of natural fibers could able to offer good resistance against the sliding load. This may increase the high interfacial temperature leading to high frictional effects at the interacting surfaces. But the hybrid effect of PP/30 composites exhibited least COF among the composites.

3.1 Morphology of the Worn Surfaces

The SEM image of the worn surfaces under the action lower and higher sliding pressure is shown in fig. 4(a - d). It is observed that in all the worn surfaces, the plastic deformation of the matrix was common. Further, the worn surface exhibits the abrasive behavior under all the conditions of sliding actions.

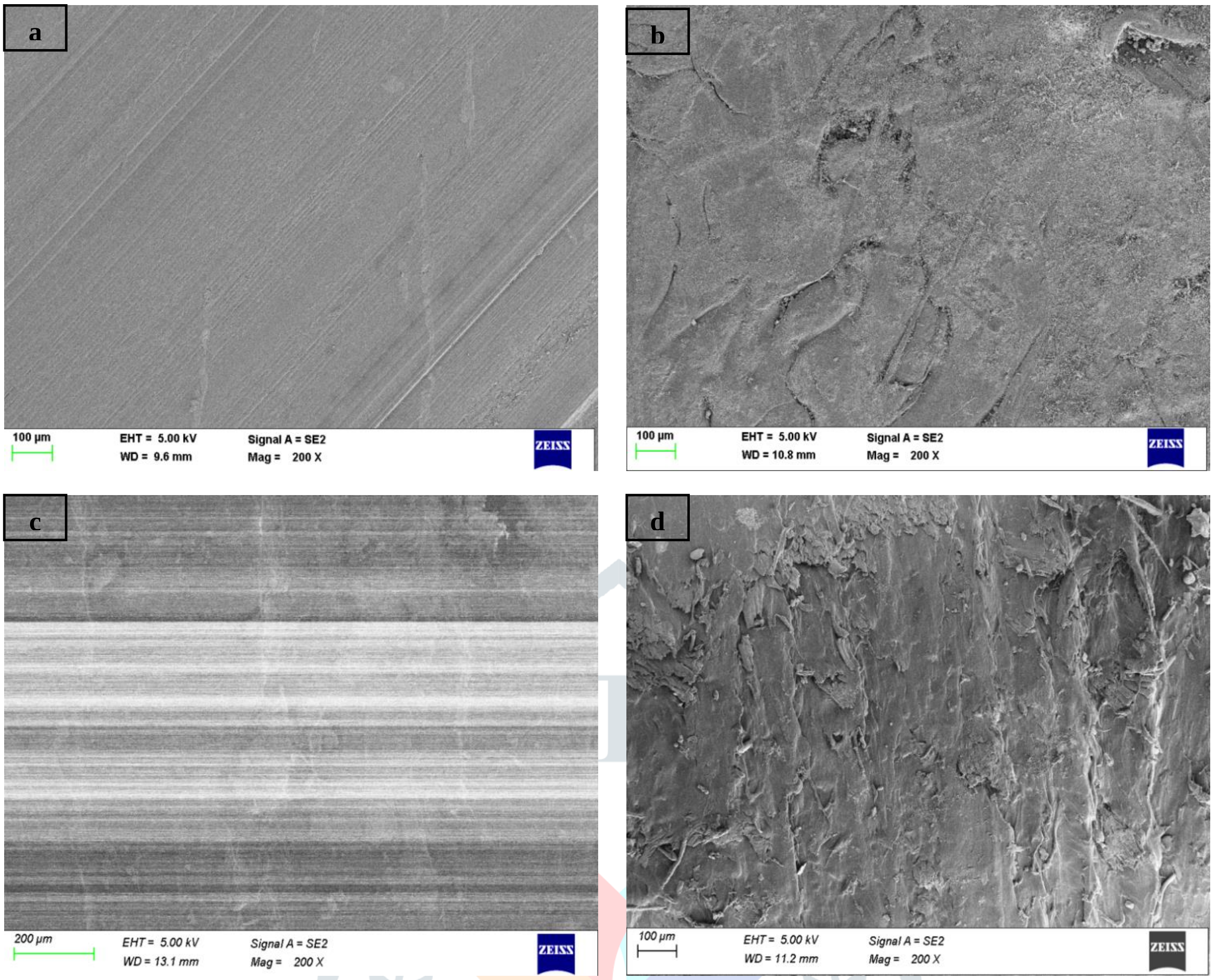


Figure 5: SEM images of the worn surfaces under the action of sliding pressure: a) Neat PP (25 N), b) Neat PP (100 N), c) PP/10 composites (25 N) and d) PP/10 composites (100 N)

The SEM image of the worn surface of neat PP under the action of varying sliding pressure is shown in fig. 5(a and b). It is observed that at lower pressure neat smooth surface is seen as a result of lesser deformation. Smooth parallel wear tracks are seen on the surface. The slight uniform deformation of matrix is exhibited by the figure. Further, the semi crystallanity of neat PP is not exposed at this stage (Fig (a)). But the effect of higher pressure is exhibited in the fig.5 (b). The deep penetration is observed due to heavy deformation. Small pits are seen across the surface due to overheating as a result of cracks in the system. The semicrystallanity of PP is clearly exhibited in the figure. But still localized stress areas are rarely reported on the worn surface. The worn surface of PP/10 composites under the action of lower pressure exhibits uneven surface with neat sliding (Fig.5(c)). But the effect of penetration is still less.

But at higher pressure (Fig.5d)), the deep parallel wear tracks are seen. Further, the deep ploughing as a result of heavy pressure with broken fibers is seen on the surface. The matrix wear debris is more compared to broken fibers. The agglomeration of wear debris along with deformed matrix is seen across the surface.

The SEM images of the worn surfaces as an effect of varying sliding pressure of PP based natural composites are shown in fig. 6 (a - d). Smooth texture surface is observed as an effect lesser pressure in PP/20 composites (Fig.6 (a)). But the slight deformation of the matrix across the sliding zones is seen. But severe plastic deformation with slight uneven surface is exhibited by PP/20 composites (Fig.6 (b)).

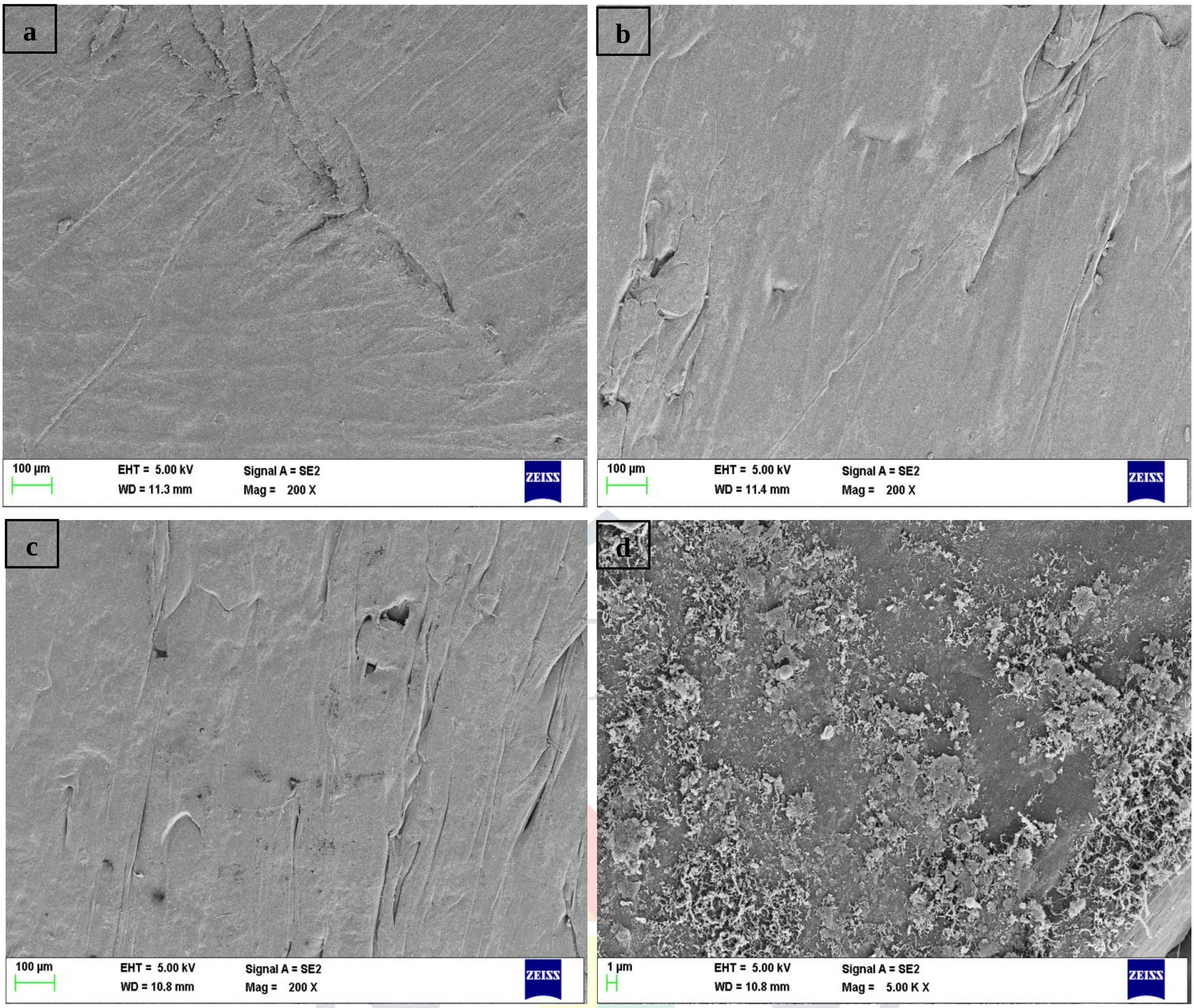


Figure 6: SEM images of the worn surfaces under the action of sliding pressure: a) PP/20 composites (25 N), b) PP/20 composites (100 N), c) PP/30 composites (25 N) and d) PP/30 composites (100 N)

The localized stress concentration areas are seen on the surfaces. This may due to overheating of the surface due to high frictional temperature. But similar observations are made on the worn surface of PP/30 composites under the action of lower pressure (Fig. 6(c)). The interrupted wear tracks are observed on the surface due to effective support of hybrid fibers. Small patches of worn surfaces are seen as result of non –resin zones in the system. But severe abrasive action mechanisms are seen on the surface of PP/30 composites (Fig. 6(d)). The agglomeration of small broken fibers is seen on the surface along with the matrix wear debris. It is clear from the figure that fiber sliding has contributed to critical wear volume loss of composites. Further, it is observed that the abrasive broken fibers of the surface has supported completely in resisting the applied sliding load. But the integrity of natural fibers with polypropylene is appreciable in this condition. Small patches are seen on the surface as a result of overheating. But the effect of sliding pressure is seemed to be very moderate due to combined effect of hybrid fibers.

IV. Conclusion

Investigation on the effect of sliding pressure on the wear behavior of PP based Ramie –Sisal fiber reinforced polymer composites has been studied and reported. During the study, following conclusion was drawn:

1. The combined effect of Ramie fiber and Sisal fiber is most appreciable in defining the wear resistance of Polypropylene based natural composites
2. The sliding wear behavior of PP/10, PP/20 and PP/30 composites was studied by varying the sliding pressure. Neat PP exhibited the highest whereas PP/30 composites exhibited the least wear volume loss
3. The wear response of these composites have followed the liner trend and wear volume loss increases with increase in sliding pressure
4. The specific wear rate of all the composites decreases with increase in sliding pressure
5. The coefficient of friction decreases within increase in pressure and fiber loading
6. At high pressure, neat PP was subjected to severe friction whereas PP/30 composites experienced least COF
7. Morphology of the worn surfaces reported that critical wear volume loss is due to wear of both fiber and matrix

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