Tribological properties of *Cyperus pangorei* fibre reinforced polyester composites

(Friction and wear behaviour of *Cyperus pangorei* fibre/polyester composites)

Abstract

This paper investigated the tribological behaviour of natural fibre reinforced polyester composites. The *Cyperus pangorei* (CP) fibre and and polyester were used as a reinforcement material and thermosetting matrix, respectively. The composites were fabricated using compression moulding technique with 40 wt.% of CP fibre. Technological properties such as density, hardness and wear of the composite specimens were determined. The density and shore D hardness of the prepared specimens were 1.0176 g/cc ±0.106 and 87.25 ±4.1, respectively. A pin on the disc wear test machine was used to conduct the dry sliding wear test with constant sliding distance, various sliding velocities of 1, 2 and 3 m/s, and a range of contact pressure of 0.13 – 0.38 MPa. After the wear test, the surface roughness of worn specimens was measured. The specific wear rate increased when the applied load was increased on the specimen. A non-linear decrease in coefficient of friction (COF) was observed with the combination of increasing contact pressure and decreasing sliding velocity. The morphological analyses were carried out using a scanning electron microscope (SEM) for the worn specimens.

Keywords: natural fibre, hardness, surface roughness, specific wear rate, coefficient of friction, wear.

Acronyms

ASTM	- American society for testing and materials
COF	- Coefficient of friction
CPFPC	- *Cyperus pangorei* fibre reinforced polymer composites

CPF - *Cyperus pangorei* fibre

HRC - Rockwell hardness (C-scale)

NFRPCs - Natural fibre reinforced polymer composites

PLA - Poly (lactic acid)

SEM - Scanning electron microscope

Introduction

Generally, the natural fibre reinforced polymer composite (NFRPC) material has gained more attention due to their light weight and high specific strength characteristics, among other inherent properties. In recent years, the natural fibres are prefered as reinforcement materials with polymer matrix for small scale applications, due to some advantages, such as biodegradablility, lower density, easy availability and lesser harmful to human being when compared with the synthetic fibres. Moreover, the reinforcement characteristics of natural fibres obtained from the renewable energy sources have supported the composite production industries to perform and maintain their social responsibilities and eco-friendly ambience. Also, these natural fibres are very favourable to the fabrication of eco-friendly product (Nirmal *et al* 2015, Mahesha *et al* 2017).

Nowadays, the polymer composite materials are widely used in various engineering applications or fields.These include, but are not limited to, aerospace, construction, sports, automobile, and marine fields. These materials are used in static and dynamic loading conditions, such as bearing cages, seals, bushes, clutches cams, roller, wheels, to mention but a few (Omrani *et al* 2016, Harsha and Tewari 2004). Each polymer has different tribological behaviour. It is essential to study the tribological characteristics of fibre reinforced polymer composites to prevent the catastrophic failure of materials due to the excessive frictional force (Bajpai 2013). Friedrich *et al* (1985) investigated the tribological behaviour of fibre reinforced composite materials under different conditions. They concluded that the short fibre filled polymer composite did not offer better tribological properties. When adding long fibre with a polymer resin, it exhibited a better wear rate and wear resistance (Friedrich and Cyftka 1985). Many studies have been carried out on tribological analysis of NFRPCs, such as kenaf/epoxy composites (Chin and Yousif 2009), sugarcane fibre reinforced polyester (SCRP) (El tayeb 2008), betelnut fibre reinforced polyester composites (Olga and Tomasz 2017, Nirmal *et al* 2010) cotton/polyester (Gill and Yousif 2009), sisal/phenolic resin (Hashmi *et al* 2007).

Furthermore, other natural fibres, such as jute, coir, oil palm, bamboo, waste silk, hemp and banana (Bledzki *et al* 2007, Xin *et al* 2007, Joseph *et al* 2002, Rana *et al* 1999) have proved to be an effective reinforcement natural fibre materials in the thermoset and thermoplastic matrices. Nevertheless, in some circumstances, such as viscoelastic, viscoplastic or time-dependent behaviour due to creep and fatigue loadings, the performance of NFRPCs has not been well explored (Manikandan *et al* 1996, Jacob *et al* 2004). Several studies have been focused on the mechanical properties of NFPRCs, concerning the interfacial adhesion between the fibre and the matrix (Olga and Tomasz 2017). A few works have investigated the tribological performance of natural fibre reinforced composite material (Pothan *et al* 2003, Pothan *et al* 1997, Gassan 2009). The tribological behaviour of composites with the reinforcement effect of sisal fibre in phenolic resin was studied for brake pad application. They concluded that the sisal fibre composite could be a suitable alternative to the asbestos used in the brake pad system (Xin *et al* 2007). Olga and Tomasz (2017) investigated the hardness and tribological properties of the wood-polymer composite. They fabricated the composites with wood flour as a reinforcement material and poly (lactic acid) (PLA) and polypropylene as matrix materials. They obtained highest Brinell's hardness for dry samples compared to wet samples. They observed that the friction coefficient decreased with an increase in wood flour content in polymer composites (Olga and Tomasz 2017). Thus, they noticed that the most important component of the composite for this application is the polymeric resin.

Though there are many studies available on the tribological aspects, using natural fibre composites. Still, combination of new materials needs to be explored towards achieving a high performance as well as an improved light weight bearing material. Hence, in this work, the composites were fabricated with the combination of *Cyperus pangorei* short fibre (CPF) and polyester matrix, using optimum fibre loading and fibre length conditions obtained from the previous work (Mayandi *et al* 2019). This work aimed at investigating the physical properties and tribological behaviour of CPF reinforced polyester composites. The influence of CPF on the tribological behaviour of the polyester matrix was studied for different operational parameters: varying sliding speeds and normal loads. The SEM morphological analysis and surface roughness studies were performed on the worn out surface of the composite samples to understand the wear failure mechanisms.

Materials and experimental procedures

Cyperus pangorei fibre

The composite materials were fabricated using *Cyperus pangorei* fibre (CPF). *Cyperus pangorei* (Figure 1) is a tropical plant available in the river margin to the length of 50-90 cm. It is probably native of India or Srilanka, but also found in Africa and Southeast Asia. The plant is widely used for making mats in India. It is especially well known for making 'Pathamadai' mats in southern India. These are commonly called Korai in Tamil local language. This plant is grown well in irrigation canal, sides of and inside rivers. This plant was collected from Pappankulam and Pathamadai of SouthTamilnadu, South India. The fibre extraction process from the stem of *Cyperus pangorei,* using the retting process is presented in Figure 1. The detailed extraction process was reported in our earlier work (Mayandi *et al*

2016).

Figure 1. (a) Harvested plant stem of *Cyperus pangorei* (b) The plant immersed in water (retting process) (c) The fibre removed from wet stem using hand extraction method (d) The dried fibre.

Polymer matrix material

Commercially available and easily accessible unsaturated polyester (UP) isophthalic resin matrix (grade 4502) was procured from Vasavibala resins (P) Ltd, Chennai, India (Krishnan *et al* 2018, Nirmal *et al* 2010, Hashmi *et al* 2007). The polyester resin in liquid form contains monomers, which was converted into a rigid phase (complex cross-linked molecules) after the room temperature curing process. The main role of the polymer is to bind with the fibre and protect the fibres from the environmental and processing conditions. Generally, the polyester matrix is available in form of viscous, pale coloured liquids. It consists of a solution of polyester in a monomer, usually a styrene. The MEKP acted as catalyst and cobalt naphthenates acted as an accelerator for curing the polyester. The accelerator and catalyst are used to initiate and accelerate the curing process of the polyester matrix. Since the amount of accelerator and catalyst can affect the curing time of the polyester matrix. In this work, 1.5 ml of MEKP and cobalt naphthenate was used for the 100 ml of resin, as suggested by the resin manufacturer.

Fabrication of composite materials

The fabrication of the composite plate was made using compression moulding with an application of hydraulic pressure to close the mould. Figure 2 shows the fabrication process of *Cyperus pangorei* fibre polymer composites (CPFPC).

Figure 2. (a) Extracted fibre stored in container (b) Random fibre orientation in the bottom of moulding die (c) Fibre compressed using compression moulding machine (d) Ejected composite plate from die.

Firstly, the polishing wax was applied on the mould for the easy removal of the laminate after fabrication. The mould cavity size of 300 mm x 150 mm was used for the fabrication of the composite laminates, with 3 mm thickness. After that, the fibre was cut into a length of 40 mm long. Then, the required amount of 40 mm sized fibres was randomly oriented in the mould cavity and subjected to the precompression for about 20 to 30 minutes for making a fibre mat. İn a first step, the polyester matrix was prepared with 1.5 ml of each MEKP, cobalt naphthenate and 100ml of the polyester matrix for the room temperature curing (Pokhriyal *et al* 2017). During the mixing process, the catalyst was thoroughly mixed or added in the polyester matrix before the accelerator. In the second step, a 500 ml of the polyester mixture was poured over the 53 gram of fibre mat placed in the mould cavity to ensure a complete wetting of all the fibres. Then, the mould cavity was closed with the top mould by applying pressure of 15 MPa and left for room temperature curing for about 4 to 5 hrs. The excess resin was coming out from the mould after the compression through the orifice provided in the lower mould. The cured specimens were cut into the square shape with 20 mm x 20 mm size in accordance with the ASTM standards. The weight percentage of the fibres in the composite plate was calculated as 40 ±2 %.

Density test

The specimens were prepared from the fabricated composite plates according to the ASTM D792 standards. The Mettler Toledo densitometer machine was used to measure the density of the prepared composite. It was used with water as the immersing liquid. Based on the ASTM standards, measurement of the density of CPFPC was performed on five samples. The average density of the CPFPC composite was determined and reported.

Hardness test

The digital shore D hardness machine was used to measure hardness of the CPFPC. The measurements were carried out on 3 mm thick specimens of CPFPC on a Shore-D scale according to ASTM D2240 standard (Karthikeyan *et al* 2016). Measurement of hardness of the CPFPC was conducted on ten samples. The indentations were made at ten different locations for each specimen, and the average hardness value was calculated and shown in later in Figure 4.

Surface roughness test

The surface roughness test was carried out using the portable surface roughness tester of Mitutoyo Surftest SJ-410 Series. The tracing length on the specimen surface was fixed as 7.02 mm. Furthermore, surface roughness measurement was carried out considering both tracing length and cut-off length as same as using low pass filter option. Due to the capacity of the probe movement, the tracing length was fixed as 7.02 mm instead of 8 mm. The worn out surfaces of the composite samples were subjected to surface roughness test. The surface roughness parameters R_a, R_q, R_z, R_p and R_v were taken from the equipment. Where R_a denotes the arithmetic average of absolute values and this parameter was recorded according to ISO 4287 (1997) (Karthikeyan *et al* 2016). Similarly, R_q represents the root mean square of roughness, R_z implies the mean peak-to-valley height, R_p is the maximum height of peak and Rv depicts the maximum depth of valley were recorded following the same standard.

Wear test

A pin-on-disc (PoD) wear testing machine (Magnum Engineers, Bangalore) was used to carry out the wear test on CPFPC samples, as shown in Figure 3. The PoD machine with the following specification was used for the experimentation: Normal load range up to 200 N, frictional force range up to 200 N with a resolution of 1 N, wear measurement range from 0–4 mm, sliding speed: 0.26–10 m/s (disc speed 100 – 3000 r/min), wear disc diameter of 160 mm (EN31 disc 55-65 HRC).

Figure 3. Pin on disc wear testing machine.

In accordance with ASTM G-99, standard specimens were used to conduct the two-body wear tests. The composite pin with the size of 3 mm thick and diameter of 10 mm was used for the rubbing action. The prepared specimen surface of the composite was firmly glued at one end of the steel pin of diameter size of 10 mm and length of 27 mm, using Anabond 666 (Temperature resistant seal). A high carbon alloy steel (EN 31) with the hardness value of 62 HRC and surface roughness (R_a) of 0.54 µm was used as a counterface material for this research work. It has a high degree of hardness with compressive strength and abrasion resistance. Moreover, it is more suitable for wear-resisting machine parts and press tools. The test was conducted on a track radius of 50 mm diameter for a constant sliding distance of 1000 m, with varying loading conditions and varying velocity. Tests were conducted within the range of contact pressure of 0.13 – 0.38 MPa with varying sliding velocities of 1, 2 and 3 m/s. The friction force was measured with the help of a sensor with the lower sampling rate of 50 Hz. The arithmetic mean or average value was taken for the calculation of friction force in each test. In addition, the average value of the five samples was taken for the calculation of the coefficient of friction. Before testing, the specimen was placed inside the hot air oven at 100 °C for 1hr to ensure the removal of moisture from the samples. The initial weight of the dried sample was measured using a digital electronic balance of 0.1 mg accuracy. At the end of the test, the entire sample was again weighed individually in the same digital balance. The difference between the initial and final masses was used as a measure for wear loss. The sample was carefully placed such that the specimen was perpendicular to steel disk and parallel to the abrading direction. All the tests were conducted at a room temperature condition of nearly 32 °C and relative humidity of 52%.

Results and discussion

Density and hardness

The average density of CPFPC samples was 1.0176 g/cc ±0.106. The average value of shore D hardness for CPFPC was measured as 87.25 ±4.1. However, the variation in hareness values was oberved which may be occur due to the random orientation of CP fibres in polyester matrix. However, the composite hardness value increased by 12.3% that of the pure polyester matrix, as reported in our earlier work (Rajini *et al* 2012).

Surface roughness

Figure 4 shows the surface roughness measurement value after testing at 3 m/s sliding with varying loading conditions. It was observed that the mean surface roughness (R_a) is higher for 10 N loading condition, whereas it decreased with an increasing loading conditions. Both contact pressure and sliding velocity are independent, and both are significantly influencing the friction and wear behaviours. It mainly occurs due to the surface morphological changes, occurred in both sample and counter plate due to the asperity in contact. This can create an influence on the surface roughness profile of the worn out surface as well as the counter surface. However, the maximum PV (contact pressure × sliding velocity) limit used for this work is assumed to be not affected much on hardened counter surface material. Hence, the focus of interest turns towards the studies on surface roughness parameter for the composite samples.

Figure 4. A typical surface roughness results for 3 m/s sliding velocity with varying loading conditions.

Moreover, for a composite laminate, the surface layers are only subjected to the rubbing action which was generally a polymer phase. The change in the behaviour of polyester from rigid phase to viscous due to the generation of heat can create transfer layer formation at the counter surface. Normally, this transfer layer formation is dominant in the case of thermoplastic matrices. However, it occurred in the thermoset polymers, such as vinylester, as experienced from our earlier publication (Karthikeyan *et al* 2016) and also reported in other works (Bahadur 2000). Therefore, at lower contact pressure and high sliding velocity conditions, the polyester matrix surface layer is softened and adhered to the asperity of the counter plate. Consequently, the molecular level removal of the polyester matrix in the form of patches produced an irregular surface topography on the sample. This could be attributed to the occurrence of the high surface roughness. However, at high loading conditions, the roughness value decreased. This could be due to the polishing effect at the contact surface by the strong adhesion of transfer film with matrix and fibre debris, as reported (Golchin *et al* 2018). Since, the presence of neat polyester in the surface of composite can be subjected to the formation of debris due to the higher contact temperature. Furthermore, the peak depth and valley depth (R_z) was analysed withrespect to the varying load and varying velocity. The results obtained indicate a decrease in values of R_z at varying load for maximum velocity. It is possible to observe this result, due to the mask of debris in the valley peaks.

Tribological behaviour of CPFPC samples

The coefficient of friction for varying loading conditions is presented in Figure 5. It was evident that the specific wear rate decreased when the applied load was increased on CPFPC samples. The high value of the coefficient of friction was developed on 10 N and 20 N for the same sliding velocity of 2 m/s for both loading conditions, thereafter the friction coefficient was decreased with an increasing loading conditions.

Figure 5. The coefficient of friction for varying loading conditions.

In general, the addition of natural fibres decreased the COF of thermoset matrices. It has been reported in some works for both polyesters and epoxy matrices. For instance, CPFPC sample showed a significant improvement in the COF in comparison with pure polyester matrix, with COF or μ ranges from 0.9 to 0.95 (Yousif 2009). This could happen due to the formation of a smooth transfer layer at the interface between composite sample and counter surface. Generally, the thermal resistance of the composites can be improved with the addition of fibres in the matrix (Idicula *et al* 2006). This incresing thermal resistance can restrict the material deformation of CPFPC at the contact surface, due to the application of combined mechanical and thermal load.

At higher loading condition, the magnitude of the contact temperature between the asperity in contact got increased. Therefore, the molecular mobilty takes place at the interface between the fibre and matrix which leads to the reduction of mechanical properties. Furthermore, it leads to the formation of transfer layer by means of adhering fibre debris with valley portion of asperities in the counter surface. This can facilidate the composite samples to slide in a even surface and in turn reduce the possibility of develop high friction force. A similar result was obtained and reported by Bajpai *et al* (2013). They fabricated the natural fibre composites using *Grewia optiva* fibre, nettle fibre and sisal fibre with PLA. In all the sliding velocities, a decreased coefficient of friction was observed with an increasing normal load.

Evidently, the thermal conductivity of polyester is high (Rajini *et al* 2013), and thus the rate of heat dissipation is good. However, the transfer of heat can increase the temperature at the counter surface. Also, the addition of fibres in the polyester matrix decreased the thermal conductivity of the composite (Rajini *et al* 2013), resultantly, it decreased the accumulation temperature at the contact surfaces. Also, an increase in frictional force produced heat energy at the contact surfaces. This energy was not uniform, due to the air convection around the test rig. Hence, the interfacial bonding between fibres and matrix got weaken due to induced thermal stresses. The fibres were separated from the matrix as a result of the shearing action by the application of repeated axial thrust during sliding (Summer and Unal 2018, Yousif and El Tayeb 2008, Davim and Rosaria 2009). An increased applied load aided the detachment of fibres and peeling out of fibres from CPFPC samples during sliding on a counter plate. This is due to the high loading condition to reduce the friction coefficient (Chauhan and Kumar 2010).

The friction and dry sliding wear performance of CPFPC samples were studied, regarding the specific wear rate and coefficient of friction. The specific wear rate was calculated, using the Equation (1).

$$Ko = \Delta V /(L \times D) \ mm^3/Nm \qquad (1)$$

Where, Ko represents the specific wear rate, ΔV denotes the volume loss, L depicts the load and D stands for the sliding distance. Figure 6 shows the specific wear rate for varying loading conditions. The maximum wear rate was recorded with the sliding velocity of 3 m/s in all applying loading conditions of the samples. This was due to more fibre breaking and pulverisation on the CPFPC samples (Omrani *et al* 2016). At high loading conditions and sliding velocity, the pulverised fibre was easy to peel out, and hence the sample became deeply worn out, and specific wear rate increased with an increasing loading conditions. A similar trend was observed for the glass fibre reinforced polyetherketone peroxide composites, as reported by Harsha *et al* (2004). Moreover, Bajpai *et al* (2013) reported a similar observation on the tribological behaviour of natural fibre reinforced PLA composite. As expected, the specific wear rate was increased in all cases of sliding velocity with an increasing load. A similar result was also reported by Chin *et al* (2009). They conducted tribological test for kenaf fibre composite materials with different loading conditions of 30-100 N. They concluded that specific wear rate was affected by the fibre orientations, with respect to the sliding direction, irrespective of applied load. Accordingly, kenaf fibre reinforced polyester composite showed a higher wear performance while fibre oreintation normal to the sliding direction at all sliding velocities.

Figure 6. Specific wear rate for varying loading conditions.

Morphological analysis of worn out specimens of CPFPC

After wear testing, the worn out surfaces of CPFPC samples were examined using canning electron microscope, as shown in Figures 7 (a)-(d). The studies were performed for particular operational parameters, such as 10 N and 30 N loading conditions and sliding velocities of 1 m/s and 3 m/s. Figure 7 depicts the difference between the heterogeneous components of the CPFPC samples. The micrographs indicate the presence of fibre and the glassy structure, as the structure was represented by the matrix phase. Furthermore, Figure 7(a) indicates that smooth surfaces were formed for low loading conditions and sliding velocity. At the same time, more wear rate and uneven surfaces were produced on CPFPC samples with 3 m/s and 10 N loading conditions, as shown in Figure 7(b). The CP fibres adhered with the inner surface of the composites were exposed to the outer surface layers, due to the removal of polyester after the high velocity rubbing action. From Figure 7(b), it can be observed that the fibres were exposured at the outer layer of the composites and detached from the matrix, due to the thermo-mechanical loading (Chin and Yousif 2009) resulting from the wear test. Comparison between Figures 7(b) and (b) shows that the fibres were not separated from the matrix at high loading and high velocity conditions. This result indicates high wear resistant of CPF composites at the rubbing zone area, due to the coating layer of molten polyester and worn debris (Menezes *et al* 2011).

Figure 7. Worn out surface topography of CPFPC samples at (a) 10 N load applied and sliding velocity of 1 m/s, (b) 10 N load applied and sliding velocity of 3 m/s , (c) 30 N load applied and sliding velocity of 1 m/s and (d) 30 N load applied and sliding velocity of 3 m/s.

Comparing Figure 7(c) with (d), it was evident that Figure 7(d) depicts more rough surfaces due to high sliding velocities, and the fibre traces were visible in the same Figure 7(d). But, the fibre traces was not visible in Figure 7(c), due to the masked matrix material with a polished surface. The difference in failure was attributed to the mechanical loading, which was independent of the contact temperature. Since the magnitude of the frictional force is less in the case of low velocity condition, hence it could lead to a lower temperature at the contact surface. Evidently, the rate of degradation of the polymer depends upon the magnitude of accumulation temperature at the contact region. Among the Figures 7(a)-(d), the more rough surfaces were formed in Figure 7(b), the interface temperature increased during dry loading conditions. This phenomenon caused more damage and more specific wear rate on the composite material surface, due to the thermo-mechanical loading condition (Nirama *et al* 2010, Yousif and El tayeb 2010). These results are in good agreement with Figure 4, as more surface roughness was obtained with 10 N and 3 m/s conditioned specimens.

Conclusion

In this present work, the density, hardness, friction and wear performance of a newly developed *Cyperus pangorei* fibre reinforced with polyester composite were evaluated. The following conclusions can be drawn.

- The density and hardness of CPFPC sample were measured as 1.0176g/cc ±0.106 and 87.25 ±4.1, respectively. The hardness values were nearly the same in various point on CPFPC sample during some trials.
- A significant variation of the arithmetic mean or average surface roughness was observed at the worn out surface of composite samples. This could occur due to the mechanical interaction from asperity contacts.
- The friction coefficient gradually decreased when applied loading conditions were increased on CPFPC sample, due to the thermo-mechanical loading condition between fibres and matrix.
- The specific wear rate was more for the high sliding velocity of 3 m/s in all applied loading conditions of CPFPC sample. This could be traced to the presence of fibre breaking and pulverisation.
- The morphology analysis clearly showed the glassy matrix region in low sliding than the high sliding velocity of the CPFPC sample. Moreover, the specific wear rate was more on the high sliding velocity of 3 m/s, due to the high temperature developed between surfaces of the counter plate and CPFPC sample.
- Based on this study, the CPFPC sample offered 82% of the reduction in COF compared to the pure polyester under maximum PV limit of 1.14 MPa-m/s used in this study. Importantly, further addition of tribo fillers and nanoparticles can further decrease the

COF. Hence, this possibility qualifies the CPFPC material suitable for tribological applications.

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