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ORIGINAL ARTICLE

Physical and Wear Properties of UHMWPE Fabric Reinforced Epoxy Composites

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ABSTRACT – Usage of synthetic fiber reinforced composites has increased rapidly because of their excellent properties such that it acts as a replacement for metals in the recent days. The physical and wear properties of ultra-high molecular weight polyethylene (UHMWPE) fabric reinforced epoxy composites have been studied in this present work. Using pin-on-disc test rig, dry-sliding wear of test specimens have been tested against disc of EN31 steel material. The plain woven bi-directional 200 gsm and 240 gsm UHMWPE fabric reinforced epoxy composites were fabricated by hand lay-up method at room temperature. All the tests were conducted as per the Taguchi's L_9 orthogonal-array. The process parameters considered in the present study is load, sliding velocity and sliding time with three levels each. Specific wear rate is considered as the response variable. Optimisation is carried out to find best combination of parameters on specific wear rate. From the results, it is evident that load has greater influence on specific wear rate than other two considered parameters. Scanning Electron Microscopy (SEM) analysis was also carried out to examine the matrix distribution over fabric (reinforcement) and also their bonding between reinforcement and matrix. .

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Synthetic-fibre, UHMWPE, SEM, Taguchi, Orthogonal-array

INTRODUCTION

Usage of synthetic-fibre reinforced polymer composites (SFRPC) increased rapidly over the last two decades because of their ease in processing and lower cost. SFRPC is treated as alternate to metals and ceramics due to their exceptional properties. Most of marine, automotive and the modern aerospace industries use SFRPC, due to their excellent formability, wear resistance, and corrosion resistance [1-3].

Major constituents of fibre reinforced polymer (FRP) composites are matrix and reinforcement. Thermosetting or thermoplastic resins used as matrix material [5], and synthetic or natural fibre/fabric is used as reinforcements [9-11]. Epoxy is the most widely used thermoset matrix and most of the industries use epoxy for fabrication of composites due to their qualities like low processing temperature, thermal stability, adhesion, and hold good mechanical properties [4]. After conventional synthetic fibres like Glass fibre, Kevlar fibre, and Carbon fibre; UHMWPE fibres are most widely used as reinforcement in the recent days [5-8] because-of distinguished physical and mechanical properties UHMWPE fibres considered as third generation synthetic fibres [5-8].

UHMWPE fibres are produced by gel-spinning and ultra-drawing methods. Self-lubricating, low coefficient of friction, low dielectric constant, and resistant to UV radiation are the unique properties of UHMWPE fibre. UHMWPE fibres are chemically inert because UHMWPE are chemically resistant (excluding oxidizing acids) and alkali corrosion resistance. The density of UHMWPE fibre is approximately 0.97 g/cm^3 and posses advantages like highest specific strength, environmental resistance and long life. Due to these properties, UHMWPE fibre/fabric reinforced composite laminates replaced traditional metals and ceramics in defense, marine construction and sports utility industries.

Wang et al. [12] investigated the dynamic behaviour of plain woven 1000D fabric. The folded and unfolded UHMWPE fabric ply was subjected to impact by spherical steel projectile varying velocities from 120 to 200 m/s. The folded fabric shows considerable perforation resistance and energy absorption capacity than unfolded ply. The velocity and nose shape of the impacting steel projectile influences the performance of woven fabrics. Li et al. [13] investigated on the fibre modification of UHMWPE fibres using liquid oxidation technique. The surface modified UHMWPE fibres were used for composite fabrication and the fabricated composites were tested for tensile properties. Surface modified UHMWPE fibre reinforced composites attained better tensile properties. Cao [14] investigated on basalt fibre reinforced UHMWPE fibres with varying proportions of filler content (5-20wt.%). The fabricated composite specimens are tested for mechanical and tribological properties. From the work, it was concluded that the filler content in the composites improved both the mechanical and tribological properties.

From the above literature, it was observed that the comparison of grams per square meter (gsm) of synthetic fibre reinforced composites on mechanical and wear properties were not investigated deeply. In the present work, composites were fabricated with UHMWPE fabric of 200 gsm and 240 gsm areal densities reinforced to epoxy. The physical and tribological properties of composite specimens were investigated. Physical properties like density and water absorption

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characteristics were investigated; specific wear rate (SWR) was also investigated as part of tribological characteristic. SWR of composite test specimens were investigated under various parameters. Further optimisation was carried out using Taguchi to evaluate the best possible process parameter combination to maximise the SWR.

MATERIALS AND METHOD

Materials

The Epoxy and UHMWPE fabric were the raw materials used in the present work. Reinforcement UHMWPE plain woven fabrics of 200gsm and 240gsm obtained from Go Green Products, Chennai, India. Matrix material epoxy resin (Lapox L-12) and hardener (K-6) was supplied by Atul Polymers Limited, Gujarat, India. The properties of UHMWPE fibre/fabric are given in Table 1 while epoxy resin and hardener properties are given in Table 2.

Table 1. Properties of UHMWPE fabric.

Parameter	UHMWPE Fabric	
Areal density (gsm)	200	240
Weave	Plain	Plain
Fibre count (cm)	15.5 x 12	10 x 9
Yarn denier	600D	1000D
Thickness (mm)	0.42	0.48

Table 2. Properties of epoxy and hardener.

	Typical values	
Description	Epoxy (L-12)	Hardener (K-6)
Appearance	Clear viscous liquid	Pale yellow liquid
Density at 25 ºC (g/cm^3)	1.1-1.2	0.95-1.1
Viscosity(mpa.s at 25ºC)	9000-12000	5-15

Composite Fabrication

The UHMWPE woven-fabric reinforced epoxy composites were prepared using hand lay-up method at room temperature. Plain woven fabrics of 200 gsm and 240 gsm UHMWPE, reinforced epoxy composite panels were fabricated with varying the number of fabric layers (1 to 3). The epoxy (L-12) resin and hardener (K-6) were mixed in the ratio of 100:10 as recommended by the literature [9-11, 15]. At atmospheric condition, composite panels are cured for the duration of 24 hours. The composite laminates of both 200 gsm and 240 gsm of size 160 mm × 160 mm × 3 mm was fabricated with the glass mould of same dimensions. Wax was used as the releasing agent over the glass mould.

Physical Properties

Theoretical density of composite laminates

The theoretical density of composite laminate can be obtained from Eq. (1), from the fibre and matrix densities, and volume fractions of fibre and matrix as given in Eq. (2).

$$\rho_c = \rho_f V_f + \rho_m V_m \quad (1)$$

$$V_f = \frac{v_f}{v_c}, \qquad V_m = \frac{v_m}{v_c} \qquad [\text{‘}\mathbf{v}\text{’ is volume in cubic centimeter}] \quad (2)$$

$$W_f = \frac{\rho_f}{\rho_c} \times V_f \quad (3)$$

$$W_m = 1 - W_f \quad (4)$$

Where ρ (g/cc) and V denotes density and volume fraction, and suffix *f, m* and *c* correspond to the fibre, matrix and composite respectively. Weight fractions (W) of fibre and matrix are obtained from Eq. (3) and (4), from densities of fibre and composite, and volume fraction of respective fibre.

Void Content

Voids are formed between fabric and epoxy while fabricating composites, these voids are due to the air gaps and dust in the composite laminates. Void content can be evaluated from Eq. (5).

$$v_{void} = \frac{\rho_{ct} - \rho_{ca}}{\rho_{ct}} \tag{5}$$

Water Absorption

As per ASTM D5229 standard, the water absorption tests were carried out on composite specimens. According to standard the weight test sample should not less than 5 g. The thickness of the test specimen is maintained 3 mm, irrespective of length and width. The specimen edges are made smooth to avoid gaps between fibre and matrix. The samples were dried at 50 ºC keeping in woven for certain hours to remove pre-present moisture in the sample. The test specimens were then immersed in pure water at room condition, and at specified times the specimens were removed from the water, cleaned with neat cloth and weighed to nearest 0.1 mg and then return immediately. The tests repeated with regular time-intervals up to 30 days. Weight gain percentage of specimen is calculated using Eq. (6).

$$\mathrm{M}_t = \frac{m_{ai} - m_o}{m_o} \tag{6}$$

In the above equation, M_t is water mass gain percentage at times, m_o is mass of dry specimen before immersion, and m_{ai} is mass of specimen after immersion for respective time.

Wear Properties

Dry sliding wear tests were carried out on Ducom TR-201 (pin-on-disk) apparatus shown in Figure 1. The test specimen dimensions were tested according to ASTM G99. Load, sliding velocity, and time were the considered performance parameters. The performance parameters were arranged according to L9 orthogonal array of Taguchi design shown in Table 3, which minimises number of experiments. Specific wear rate is the response variable.

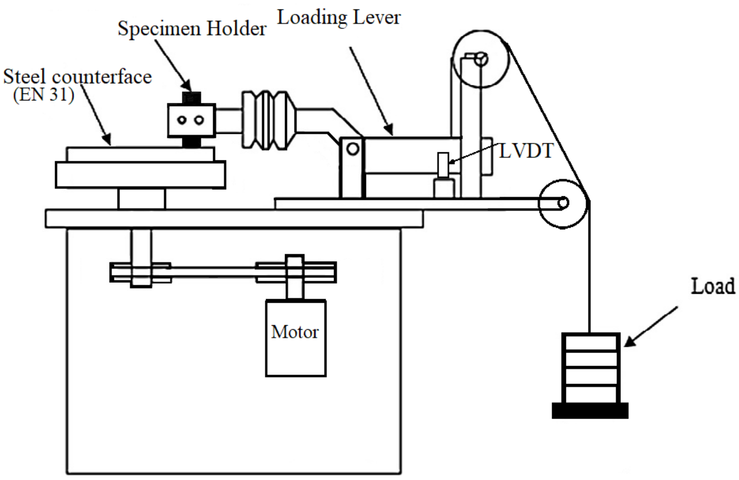


Figure 1. Schematic diagram of wear test rig.

Table 3. Levels of performance parameters.

Process parameter	Units	Level 1	Level 2	Level 3
Load	N	10	30	50
Sliding Velocity	m/s	1.57	1.88	2.19
Time	min	5	10	15

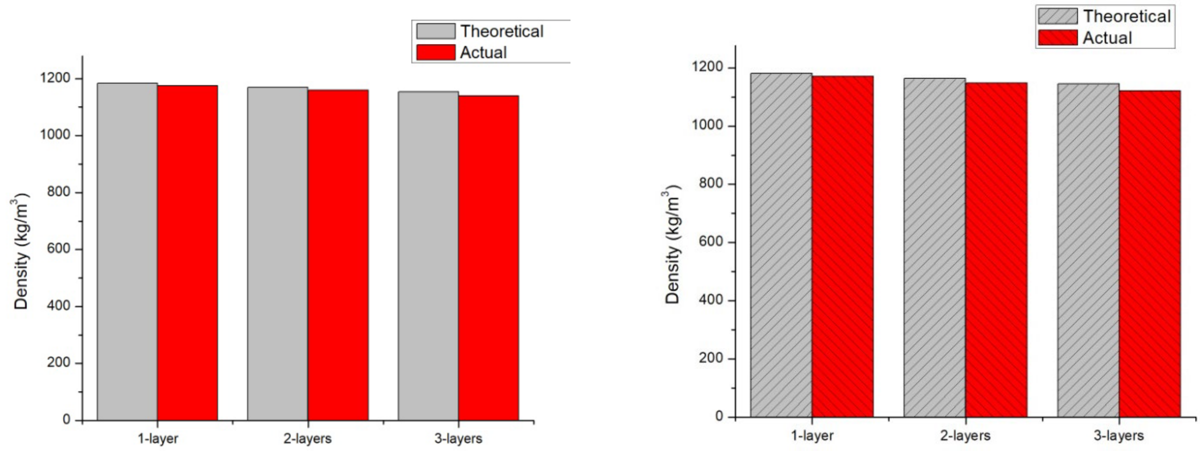
RESULTS AND DISCUSSION

Physical Properties

The theoretical and actual density of the both areal density fibre composites with varying number of layers is shown in Figure. 2. It is observed that the error between the actual and theoretical is very less and also observed that the theoretical density of the composites reduced with increase in number of layers. The reason for decrease in theoretical density is fibre mat posses lower density when compared to epoxy matrix. It can also be observed that 240 gsm fibre reinforced composites possessed less theoretical density when compared to 200 gsm. From Table.4, it is observed that volume fraction of 240 gsm fibre composite is more when compared to the volume fraction of 200 gsm fibre composite. An increase in volume fraction of 19.4% is observed for 240 gsm fibre reinforced composite over 200 gsm fibre reinforced composite. This increase in volume fraction is the prime cause for the decrease in theoretical density of the 240 gsm fibre reinforced composites.

Table 4. Physical properties.

Composite laminate	Volume fraction (%)	Mass fraction (%)	Theoretical density, ρ_{ct} (kg/m^3)	Actual density, ρ_{ca} (kg/m^3)	Void content (%)
200 gsm 1-layer	6.7	5.5	1184.59	1175.5	0.77
200 gsm 2-layers	13.4	11.13	1169.18	1159.2	0.85
200 gsm 3-layers	20.1	16.93	1153.77	1139.45	1.24
240 gsm 1-layer	8	6.57	1181.6	1170.8	0.91
240 gsm 2-layers	16	13.34	1163.2	1148.25	1.29
240 gsm 3-layers	24	20.33	1144.8	1120.5	2.12

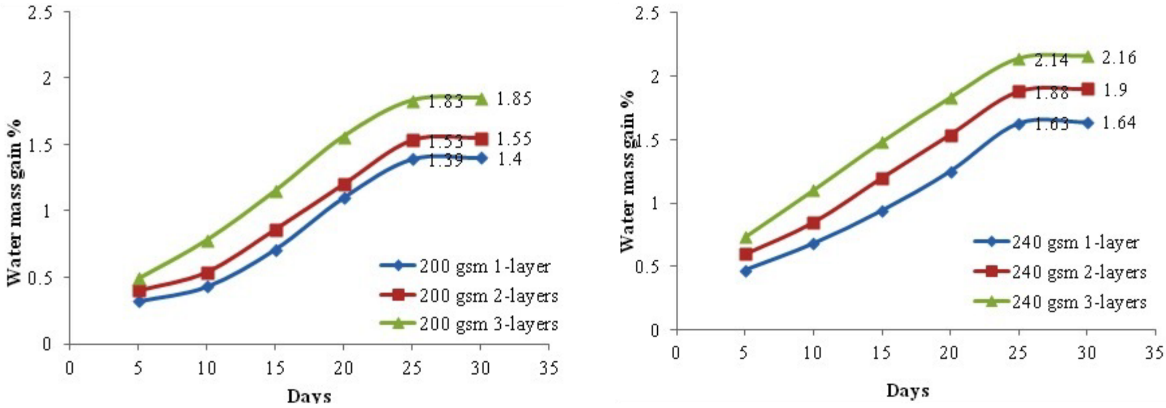


(a) (b)

Figure 2. Theoretical and actual density of composite laminate at (a) 200 gsm and (b) 240 gsm.

Water Absorption

The water absorption behaviour of UHMWPE fibre reinforced composites for both the areal densities of 200 gsm and 240 gsm by immersing the test specimens in water up to 30 days. The results are shown in Figure 3(a) and 3(b) respectively. It is evident from the Figure. 3(a) and 3(b) that the rate of moisture absorption increases with increase in number of layers and immersion time. The major reason for the increase in the moisture absorption by increase in number of layers is due to the increase in volume fraction as it can be observed from Table 4.



(a) (b)

Figure 3. Water absorption test results for (a) 200 gsm and (b) 240 gsm specimens.

Another effect of increasing water absorption rate of composites is the nature of UHMWPE fibre by capillary action and the presence of micro voids and cracks in the composites surface results in the movement of water molecules to the material by capillary action. It was observed that the increase in water absorption percentage is very less and almost constant after 25 days. Analogous results were observed by other researchers who are working in the similar lines [16-18]. Compared to the water intake percentage 200 gsm UHMWPE fibre reinforced/epoxy composite laminates with 240 gsm UHMWPE fibre reinforced/epoxy composite laminates is less. The volume fraction of 200 gsm fibre reinforced composite is less when compared to 240 gsm fibre reinforced composite; this might be the reason for the decrease in water uptake percentage for 200 gsm fibre reinforced composite.

Wear Properties

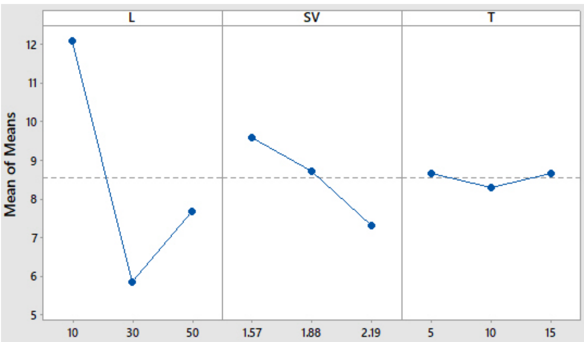
The fabricated 200 gsm and 240 gsm UHMWPE fibre reinforced composites were tested for wear behaviour using pin-on-disc test apparatus. The obtained results are tabulated in Table 5. The tests were carried out by varying three controllable parameters with three levels each. The tests were performed as per the Taguchi's L_9 orthogonal array (OA). OAs helps in shaping the possible combinations of factors and identifying the paramount combination. The Taguchi technique reduces the experimental costs by simultaneous study of the parameters in large number.

Table 5. Specific wear rate of test specimens of composite laminates

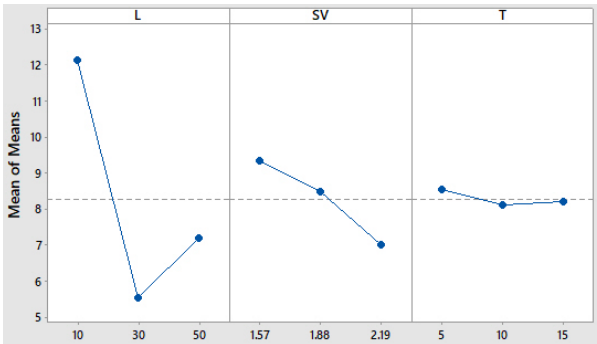
S.No	Load (N)	Speed (rpm)	Time (min)	Specific Wear rate x 10^{-5} $mm^3/N.m$					
				200 gsm			240 gsm		
				1-layer	2-layers	3-layers	1-layer	2-layers	3-layers
1	10	1.57	5	13.742	13.757	13.726	14.251	14.283	14.251
2	10	1.88	10	11.861	11.861	11.848	11.928	11.861	11.941
3	10	2.19	15	10.742	10.753	10.7648	10.742	10.7534	10.7648
4	30	1.57	10	6.4225	6.3758	6.2633	6.3163	6.0509	5.7856
5	30	1.88	15	6.6223	5.9827	5.8067	5.984	5.8511	5.6738
6	30	2.19	5	4.5282	4.2272	3.9574	3.9954	4.0145	3.7671
7	50	1.57	15	8.6695	7.8733	7.3885	8.4713	8.3121	8.0892
8	50	1.88	5	7.7207	7.6197	6.4894	7.3138	7.1277	7.1011
9	50	2.19	10	6.6591	6.0883	5.3881	6.5068	6.2557	6.1872

Control Parameters on Specific Wear Rate

The design matrix along with their controllable factors and responses are shown in Table 5. The effect of each controllable variable can be studied on specific wear rate with the help of main effect plots and their interaction plots [15, 19]. The main effect plots for 200 gsm and 240 gsm fabric reinforced composites are shown in Figure 4 and 5 respectively. The level at which mean of means is highest that gives the highest SWR and that particular combination of controllable parameters is taken as optimum as per the Taguchi optimisation technique. From Figure 4, it is observed that lowest load, lowest sliding distance and lowest time is considered as the best parameters combination for SWR of 200 gsm UHMWPE fibre reinforced composites. Similarly, from Figure 5, it is observed that lowest load, lowest sliding distance and lowest time is considered as the best parameters combination for SWR of 240 gsm fibre reinforced composites as well.



(a)



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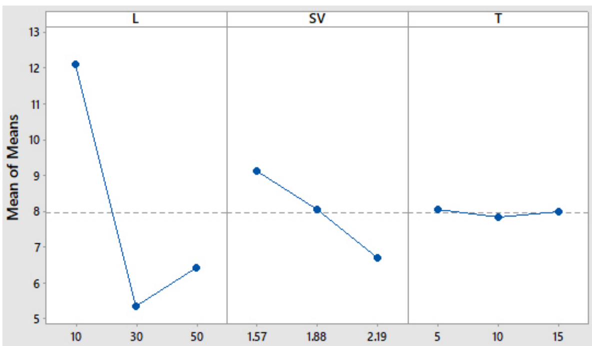


(c)

Figure 4. Main effect plot of 200 gsm at (a) 1-layer, (b) 2-layers and (c) 3-layers fabric reinforced composites for specific wear rate.

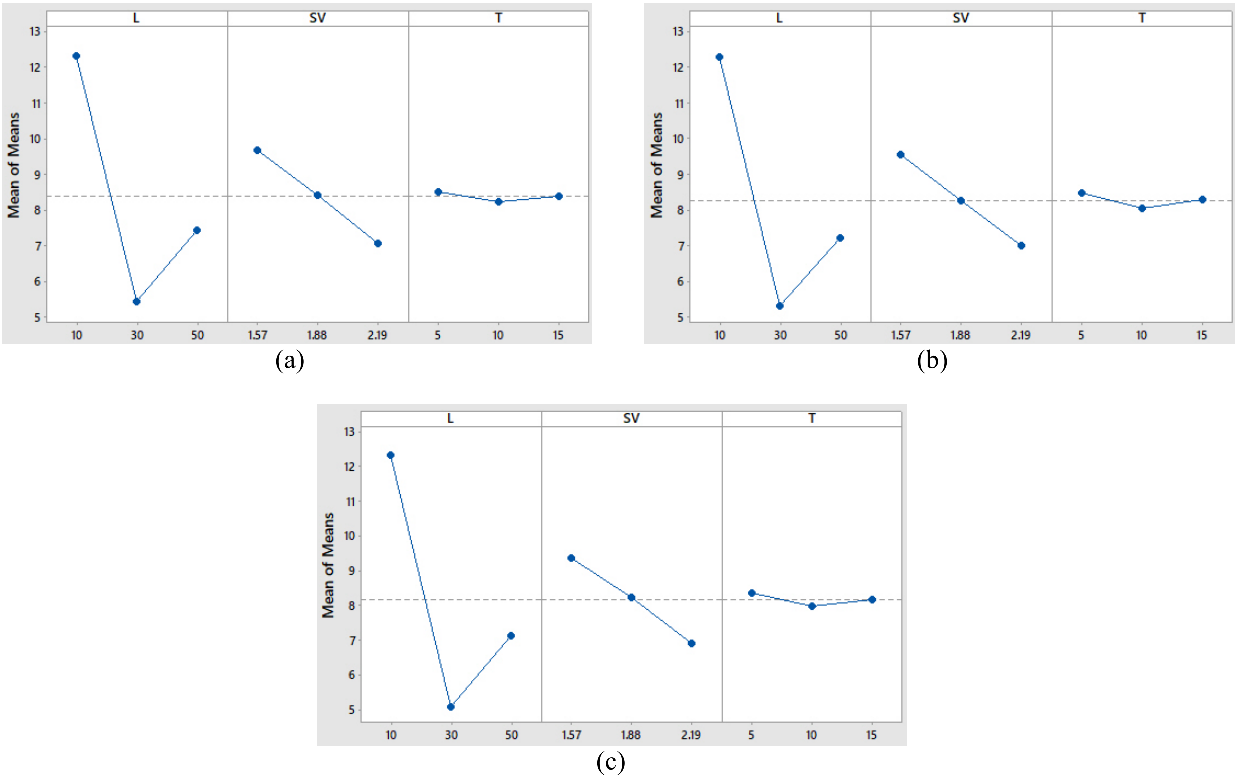


Figure 5. Main effect plot of 240 gsm at (a) 1-layer, (b) 2-layers and (c) 3-layers fabric reinforced composites for specific wear rate.

Statistical Analysis of Variance

ANOVA is used to know the process parameters influence and their percentage contribution on the responses [20]. Based on the mean effect plots, it is understood that the three different layers effect on the SWR is similar. For this ANOVA is carried out for only three layered composite specimens of both 200 and 240 gsm areal density UHMWPE fibre reinforced composite specimens. The ANOVA results of both the composites are tabulated in Table 6. It is observed that only load has significant effect on the response (SWR) since its P-value is less than 0.05, the other two parameters has no influence on the response variable since its P-value is more than 0.05. The percentage contribution of load on SWR for 200 gsm composite is 89.9%, followed by 10% for sliding velocity and 0.1% for time. For 240 gsm composite, the percentage contribution on SWR for load is 89.8% followed by 9% for sliding velocity and 1.2% for time.

Table 6. ANOVA table for specific wear rate of 200 gsm and 240 gsm fibre reinforced composites

Source	200 gsm					240 gsm				
	DF	Adj SS	Adj MS	F-Value	P-Value	DF	Adj SS	Adj MS	F-Value	P-Value
L	2	79.3955	39.6977	141.35	0.007	2	83.6469	41.8235	65.83	0.015
S	2	8.8386	4.4193	15.74	0.06	2	9.1636	4.5818	7.21	0.122
T	2	0.0789	0.0395	0.14	0.877	2	0.2422	0.1211	0.19	0.84
Error	2	0.5617	0.2808			2	1.2707	0.6353		
Total	8	88.8747				8	94.3235			
Model Summary						Model Summary				
S	R-sq	R-sq (adj)	R-sq (pred)			S	R-sq	R-sq (adj)	R-sq (pred)	
0.529944	99.37%	97.47%	87.20%			0.797085	98.65%	94.61%	72.72%	

Effect of Sliding Velocity on SWR of Composites

Figure. 6 and 7 represents the SWR of the 200 gsm and 240 gsm UHMWPE fibre reinforced composites respectively. From Figure. 6 and 7, it is observed that the SWR decreases as the sliding velocity increases at higher load (50 N), whereas at 30 N load; the SWR decreased initially and increased further due the accumulation of wear out particles on to the sample again. SWR is lower at higher sliding velocities at higher loads; similar results were observed by others researchers who worked in similar lines [21-23].

Moreover, SWR is almost equal for both 200 gsm and 240 gsm UHMWPE fabric reinforced composites. The wear of the specimens is very less due to the good bonding behaviour of the matrix and the reinforcements. The bonding between the fabricated and wear tested specimens were observed using SEM. The bonding between the matrix and reinforcements are the prime reason for attaining higher wear resistance and moreover the strength of the synthetic (UHMWPE) fibre reinforced composite is also one of the reason.

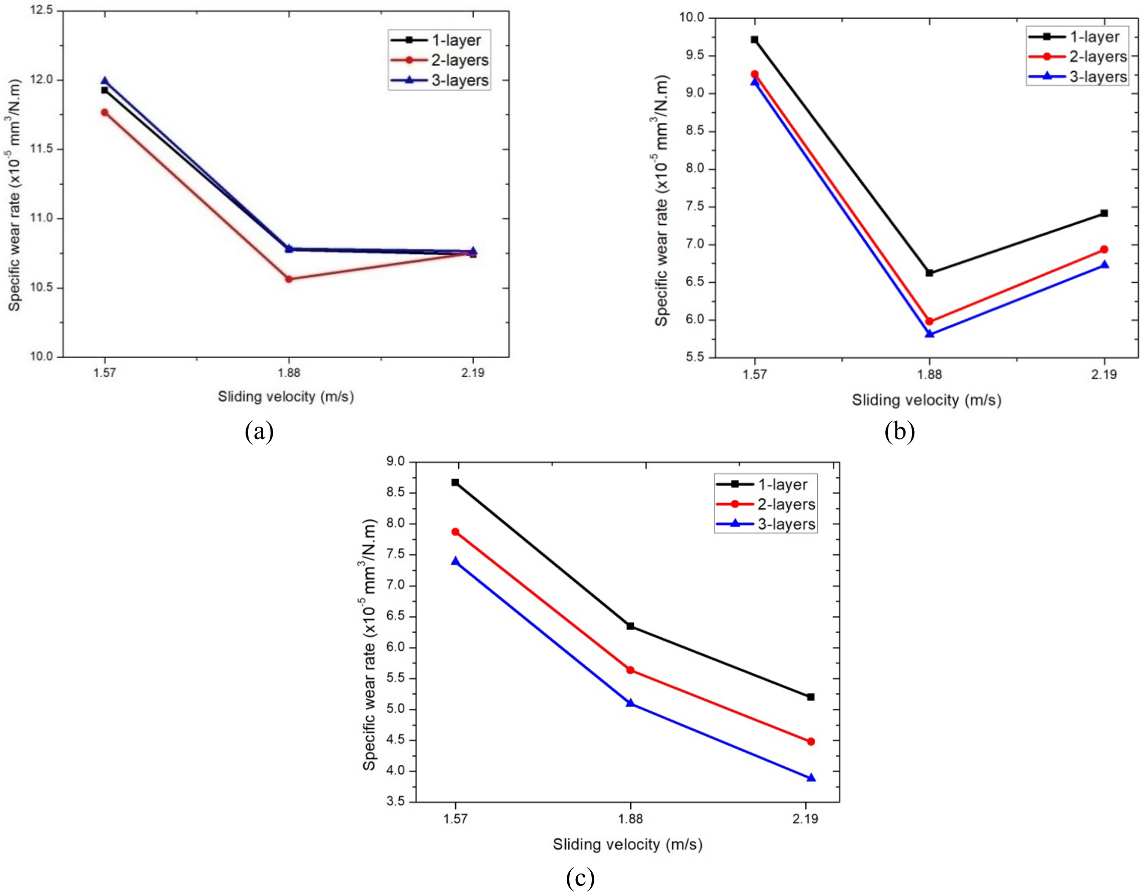


Figure 6. Variation of SWR for 200 gsm fibre reinforced composites at (a) 10 N, (b) 30 N and (c) 50 N load.

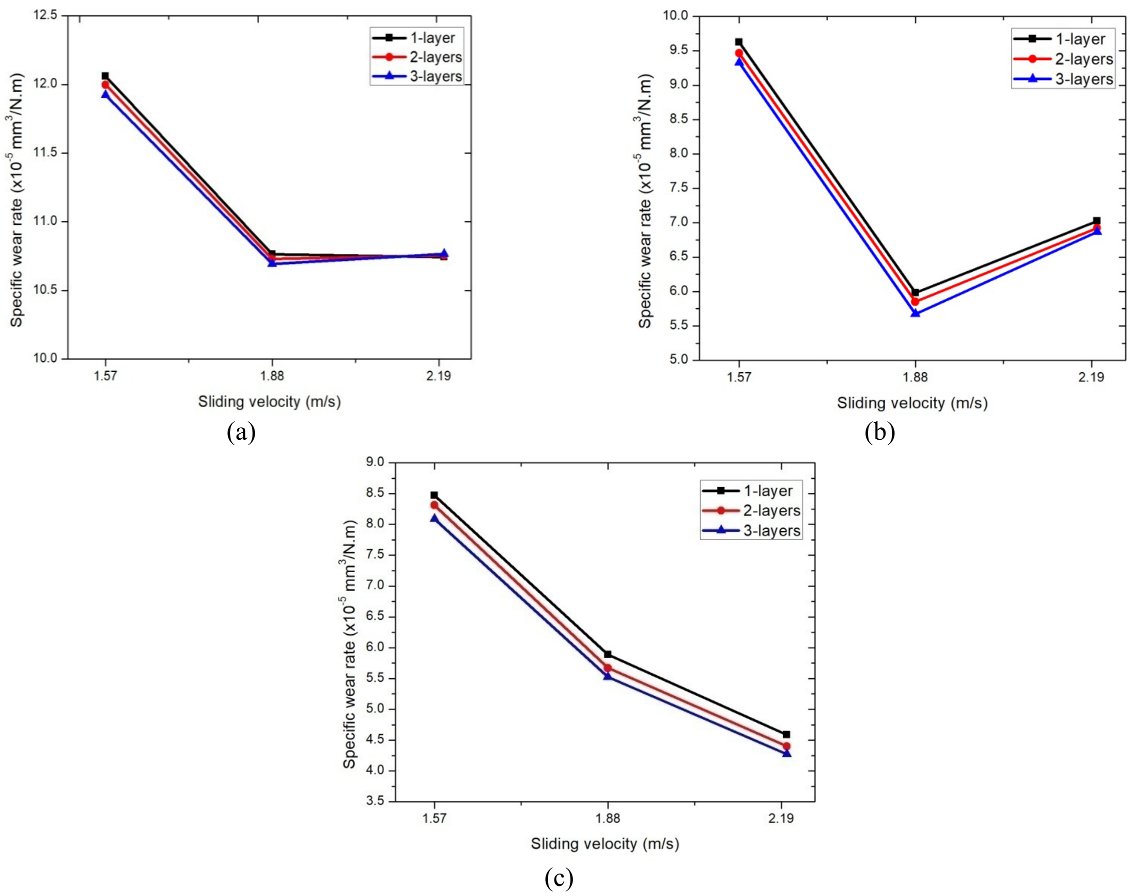
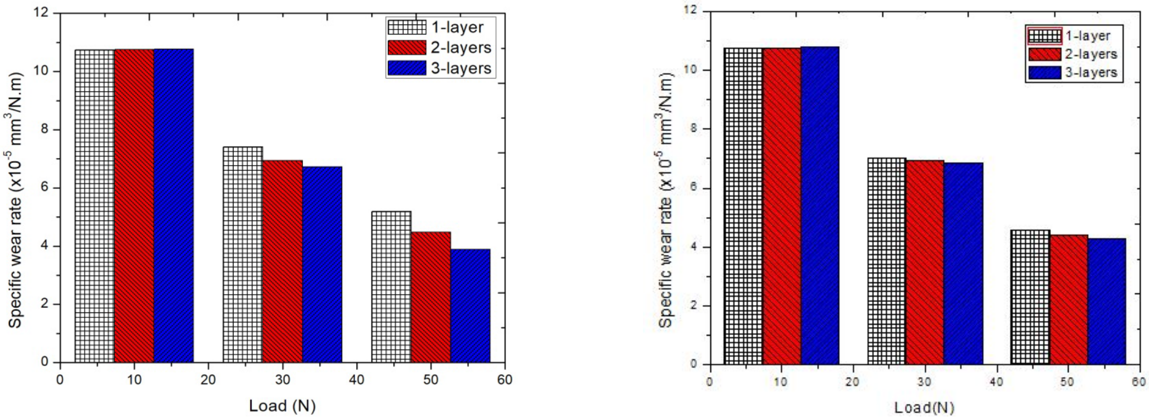


Figure 7. Variation of SWR for 240 gsm fibre reinforced composites at (a) 10 N, (b) 30 N and (c) 50 N load.

Effect of Load on SWR of Composites

The effect of load on SWR of the fabricated composites at higher sliding velocity is shown in Figure 8 (a) and 8(b). The SWR for both 200 and 240 gsm UHMWPE fibre reinforced composite specimens is equal in both the composites; the SWR is decreased with increase in load as is observed from the Figure 8 (a) and 8(b). Similar results were observed by other researchers who worked on similar lines [24-27]. The effect of layers on the SWR is almost equal for both the composite specimens since the wear of the composite took place only on the outer surface as is observed from the SEM images. The reduction in SWR for 3 layered composite specimens is 50% for 30 N load when compared to 10 N load. For 50 N load it is observed as 62 % reduction in SWR when compared to 10 N load for 200 gsm fibre reinforced composites. For 240 gsm UHMWPE fibre reinforced composites, the reduction in SWR for 3 layered composite specimens for 30 N load is 34.5% when compared to 10 N load and for 50 N load is 55% when compared to 10 N load.

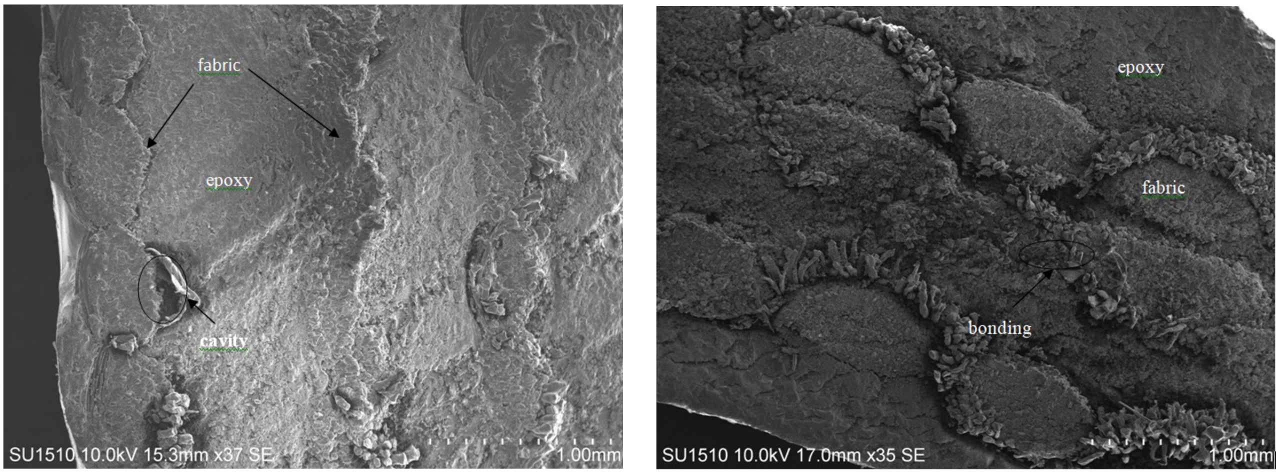


(a) (b)

Figure 8. Variation of SWR at different loads for (a) 200 gsm and (b) 240 gsm of UHMWPE fibre reinforced composite specimens.

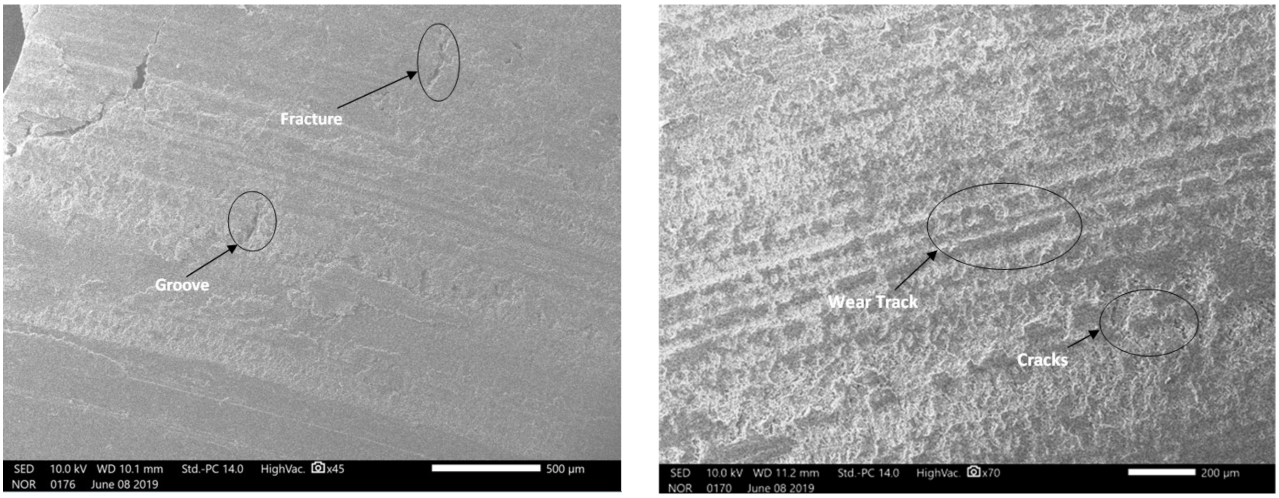
SEM Analysis

Investigation of both fractured and worn out surfaces of the two different areal density fibre reinforced composites is shown in Figure 9 and 10 respectively. The Figure. 9 (a) and 9(b) represents the good adhesive bonding between the matrix and reinforcement. Fibre pullouts and casting defects are no where existed in the figures. Small voids are available in Figure 9(a) which indicates the insufficient matrix distribution in that particular region.



(a) (b)

Figure 9. Fractured SEM image of (a) 200 gsm and (b) 240 gsm fibre reinforced composites.



(a) (b)

Figure 10. Wear tested SEM image at 200 microns of (a) 200 gsm and (b) 240 gsm fibre reinforced composites.

The wear tested samples illustrated in Figure 10 (a) and 10(b) in which the scratches and smearing are observed, are the major characteristics of sliding wear phenomena. It is observed that there are some wear grooves, fractures, and matrix cracks in the worn surfaces after undergoing wear test in 200 gsm fibre reinforced composites as is evident from Figure. 10(a). Similar results were observed by other researchers who worked in the similar area of wear testing of composites [28]. The SEM image of the 240 gsm fibre reinforced composite exhibited the smooth grooves with fine and closely spaced wear track. The plastic deformation of the epoxy matrix is restricted by the reinforced fibre such that less wear is observed.

CONCLUSION

A total of six different composite specimens were fabricated with varying the number of layers (1, 2 and 3) and also with the areal densities of the fibre mat (200 and 240 gsm). The physical and wear characteristics were investigated on the fabricated specimens and the following conclusions were drawn:

i. The theoretical and actual density of the composites reduced with increase in number of fibre mat layers and also less theoretical and actual density is observed for 240 gsm fibre reinforced composite when compared to the 200 gsm fibre reinforced composite.
ii. The moisture absorption increase with increase in time and number of fibre layers into the composite. The 240 gsm fibre reinforced composite possessed higher water absorption when compared to the 200 gsm fibre reinforced composite.
iii. From the wear test, it was observed that the SWR is influenced only with load and has nearly 90% contribution on the SWR for both the areal densities of UHMPE fibre reinforced composites.
iv. As the sliding velocity increased, the SWR increased initially and later it is decreased due to the accumulation of wear out particles.
v. The wear of both 200 gsm and 240 gsm fibre reinforced composites is almost equal, since the bonding between the matrix and reinforcements is strong as is observed from the SEM images.
vi. The SEM images of the wear tested samples illustrated a small amount of grooves and wear tracks for both the type of composite specimens.

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