

Mechanical Properties of Multi Layer Plain Weave and 3-D Glass Fabric Epoxy Composites

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Abstract Glass fibre reinforced epoxy composites using plain weave fabric and 3D non-crimp fabric are fabricated in four different (40, 45, 50 and 55%) fibre weight fractions and their mechanical properties such as flexural strength, tensile strength, impact strength, inter laminar shear strength (ILSS) are evaluated and compared. Hand lay-up method is followed to fabricate the composite panels. Experiments suggest that the optimum fibre content is around 45% and 55% for composites prepared with plain weave fabric and 3D fabric respectively. For plain weave composite a reduction in mechanical properties is observed beyond 45% fibre content signifying the influence of fibre content and fabrication technique on the strength and performance of composites. It is seen that 3D fabric epoxy composites are stronger and exhibit higher strength with increasing fibre content.

Keywords Plain weave fabric, 3D fabric, Hand layup, Epoxy composites, Mechanical characterization

1. Introduction

Composites are materials formed with two or more chemically distinct elements, having a distinct and mechanically separable interface separating them and mixed at a macro level [1]. Unlike an alloy, the individual elements of a composite retain their properties. One or more discontinuous phases are surrounded in a continuous phase to make a composite. The discontinuous phase also known as reinforcement is usually strong and hard than the continuous phase which is referred to as a matrix. The matrix can be polymeric, metallic or ceramic. Reinforcing elements can be either particulate or fibrous. Matrix and reinforcements are chosen based on the desired mechanical properties and application. Fibres are the load bearing elements in a composite and occupy a considerable volume fraction in a composite. The matrix fixes them and keeps them at desired position and direction. It also facilitates load transfer between them and protects them from adverse environment and mechanical abrasion [2, 3].

There has been a steady increase in utilization of polymers in aerospace and automobile industries for making components like cams, brakes, wheels, seals, rollers, bearing liners, clutches, bushings, and gears since they are easy to fabricate, light in weight, possess outstanding specific strength, excellent resistance to corrosion, design suppleness as it can be tailored to suit the requirement of

the application, are self-lubricating, have superior coefficient of friction, and resistance to wear as compared to their metal-based equivalents [4-6]. Wide choice of matrices and fibres makes it very difficult to choose an appropriate combination for the given application. Among polymers, as matrices, synthetic resins like polyester, vinyl ester and epoxy are the ones which find a lot of importance over the others. Among the synthetic fibres, glass, carbon and aramid fibres have created a niche for themselves due to various reasons which include, cost, high modulus strength, stability at elevated temperatures, good impact properties, etc. Availability of fibres in various forms makes the area of composite materials even more complex, hence a comprehensive study in this field is necessary.

Laminated composites involving bi-axial type of fabric have proven their superiority in structural applications because of their balanced properties and ease in handling, but are expensive to fabricate and have poor impact resistance. A solution for these problems is a textile composite which involves fabricating net like fabric using processes like braiding, stitching or weaving. These processes produce fabric made out of integrally connected three dimensional networks of fibres. Composites fabricated using 3D fabrics have all the fibres cramped within a single fabric and so reduces labour problems like ply lay-up processes associated with bi-axial fabric. It also improves impact resistance due to presence of fibres in the thickness direction also known as binders and also due to absence of interlacing of filaments [7]. Callus P. J. et al. [7] developed 3D woven glass reinforced vinylester composites with different fibre weaving architecture. Tensile tests were conducted on composites fabricated using RTM process.

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Published online at <http://journal.sapub.org/composites>

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They observed that the mechanical properties and failure mechanisms were the same when loaded in tension, provided the fibre content in the load direction was considered. Huang Gu and Zhong Zhili [8] in their study on 3D woven composites concluded that, straight arrangement of filaments in a fabric results in a stronger composite with better dimensional stability. Lomav Stepan V. et al. [9] compared tensile properties of 3D orthogonal weave non-crimp and multi-layer plain weave E-glass composites prepared by VARTM process. They observed that absence of crimp in fabric of 3D composites resulted in higher moduli, ultimate stress and strain values than the plain weave composites.

This present work aims at evaluating and comparing the mechanical properties of plain weave multi-layered and single layered 3D orthogonal weave non-crimp E-glass fabric composites fabricated in four different fibre weight fractions using hand layup technique to gain an insight about suitability of the fabrication technique and significance of fibre content in the composite.

2. Experimental Details

2.1. Materials

In this study plain weave and 3D orthogonal weave non-crimp E-glass fabric are used as the reinforcing material. The areal densities of the plain weave and 3D fabric is 320 gsm and 1830 gsm respectively. Number of threads in warp and weft direction for plain weave fabric is 5 ends/cm. In case of 3D fabric, number of threads in warp is 8 ends/cm and in weft is 11.5 ends/cm. Both the variety of glass fabrics was procured from Fibermax Composites, Greece. The resin and hardener used in the composites are Epoxy Bisphenol-12 (Lapox – L12) and Triethylene Tetro Amine (Lapox K6) respectively. Resin and hardener was supplied by Atul Ltd., Gujarat, India. The density of the resin and hardener is 1.162 gm/cm³ and 0.954 gm/cm³ respectively [10].

2.2. Fabrication of Composites

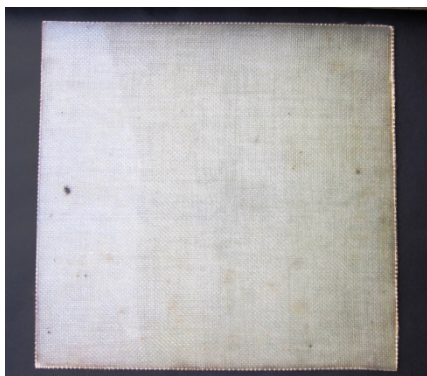


Figure 1. Plain weave composite panel

The composites were prepared using hand lay-up technique. Plain weave (PW) and 3D non-crimp E-glass fiber reinforced epoxy composite panels were fabricated in

four different weight fractions of fibres (FWF) in epoxy resin matrix. The weight fractions considered were, 40%, 45%, 50% and 55%. The resin and hardener were mixed in the ratio of 10:1 as recommended.

Curing was done under normal temperature and pressure conditions for duration of 24 hours. PW composite was fabricated with six plies of fabric, making it a multi layered composite laminate. The 3D composite comprised of a single layer of fabric. The size of all the panels was 300 mm x 300 mm having a thickness of 2.5mm as shown in Figure 1.

2.3. Mechanical Testing

2.3.1. Void Percentage

The experimental or actual density of the composites was obtained experimentally by water immersion method using the Archimedes principle. The theoretical density (ρ_t) of the composite was calculated using the Agarwal and Broutman equation [11].

$$\rho_t = 1 / ((w_f / \rho_f) + (w_m / \rho_m)) \quad (1)$$

where w_f and w_m are the weight fraction of fibre and matrix respectively. ρ_f and ρ_m are the densities of fibre and matrix respectively.

Theoretical density of the composite is calculated and related with the experimental density in order to calculate the void fraction. The volume fraction (V_{vf}) for voids is calculated using the following equation.

$$V_{vf} = (\rho_t - \rho_a) / \rho_t \quad (2)$$

2.3.2. Tensile Test

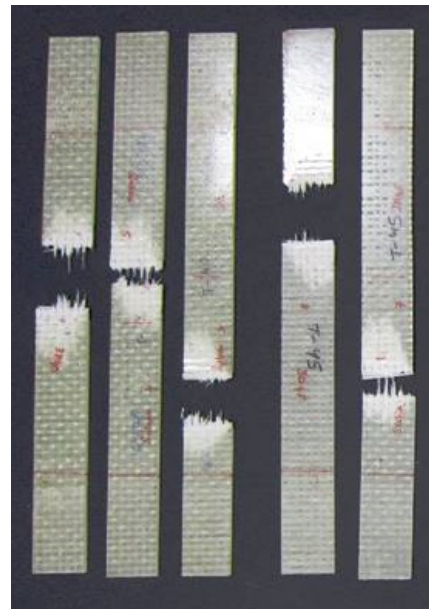


Figure 2. Tensile test specimen

Tensile tests were conducted on an Instron UTM at a constant cross head speed of 2 mm/min. The load and displacements were recorded by a data acquisition computer using software and the tensile strength was determined. Test samples according to ASTM D3039 [12] were prepared from

the cured panels. For specimen preparation, water jet cutting was used. The 3D composite panels were cut in the warp direction. The tests were conducted on five specimens each of different fibre weight fraction and an average value was considered. The specimens are presented in Figure 2.

2.3.3. Flexural Test

Flexural test was conducted to determine the flexural strength of the composites. Three point bending test procedure was adopted. The tests were conducted at a constant cross head speed of 1mm/min. Instron UTM was used for the testing and was done as per ASTM D7264 [13]. Water jet cutting was used to cut the samples from cured panels.

2.3.4. Inter Laminar Shear Strength Test

The short beam strength of the composites was determined by conducting inter laminar shear strength (ILSS) test. The aim of this test is to reduce the flexural stresses and to maximize the induced shear stress in order to estimate the shear strength of the beam. The tests were conducted on an Instron UTM as per ASTM D2344 [14]. The test procedure follows the three point bending similar to flexural test. The specimens were prepared on a jig saw composite cutting machine. The cross head speed was set to 1 mm/min. The loading was continued till either a two piece fracture was seen or the head travel exceeded the specimen nominal thickness. The machine is set in a way that it stops loading if there is a drop of load by 30% as recommended by ASTM. The specimen is presented in Figure 3.

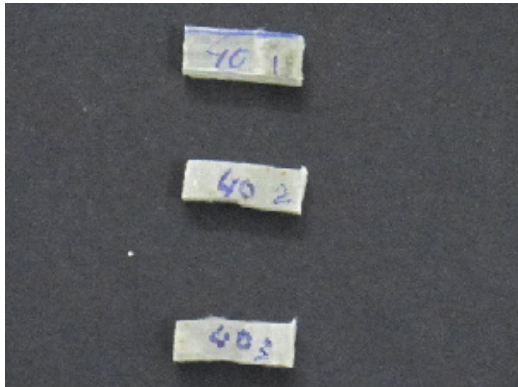


Figure 3. ILSS test specimen

2.3.5. Impact Test

To determine the impact strength of the composites, Izod impact test was conducted on specimens prepared from cured panels. The tests were conducted on a pendulum impact tester of Zwick Roell make according to ASTM D256 [15]. The specimens were subjected to impact energy of 5.5 J. The specimens of size 63.5mm×12.7mm×2.5mm were cut from the cured panel on water jet machine and notched on a jig saw machine. The test specimen after the impact test can be seen in Figure 4. The energy absorbed by the composites and the areas below the notch are considered to assess their

impact strength.

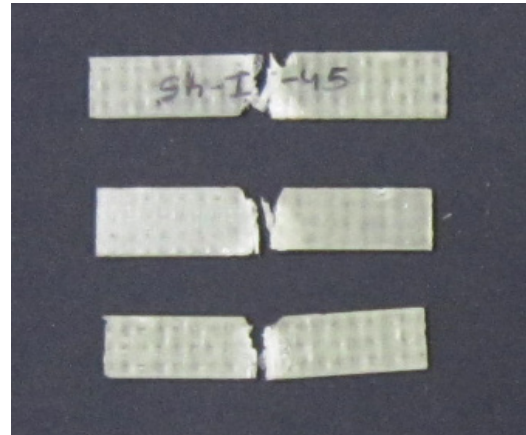


Figure 4. Impact test specimen

3. Results and Discussions

3.1. Void Proportions

Theoretical (ρ_t) and experimental densities (ρ_a) are calculated and compared. The comparison is presented in Table 1. It is evident that the theoretical and experimental densities do not match. This is expected since hand-layup technique is used for fabricating the composites. With increase in fibre content, it is observed that, the density of the composite is increasing. This is due to the fact that density of glass fibre is more than the resin.

Table 1. Theoretical and experimental densities

Fibre Weight Fraction (%)	ρ_t (g/cm ³)	PW composites		3D composites	
		ρ_a (g/cm ³)	V_{vf} %	ρ_a (g/cm ³)	V_{vf} %
40	1.43	1.39	1.32	1.35	7.22
45	1.48	1.42	2.86	1.44	4.55
50	1.50	1.44	3.94	1.51	3.49
55	1.63	1.59	2.63	1.59	2.40

3.2. Tensile Properties

The variation of tensile strength is shown in Table 2 and Figure 5. For the PW composites, it is seen that the best tensile strength is obtained for panel fabricated with FWF of 45%. The increase in tensile strength when compared to panel prepared with 40% FWF is about 28%. With increase in fibre content beyond 45%, a decline in tensile strength is observed. A drastic decline in strength is seen when the FWF is increased from 50% to 55%. Decrease in strength of the composite at higher fiber content is due to poor fiber-matrix interfacial bonding. Poor fibre-matrix interfacial bonding leads to non-uniform stress transfer, excessive movement of the fibres within the matrix, all leading to premature failure of the composites. Failure of

composites at higher fibre content can also be attributed to poor distribution of the fibers within the matrix.

Table 2. Tensile test results of PW and 3D composites

Fibre Weight Fraction (%)	Average Tensile Strength (MPa)	
	PW Composite	3D Composite
40	200.84	226.15
45	257.13	260.32
50	239.15	273.22
55	212.91	292.28

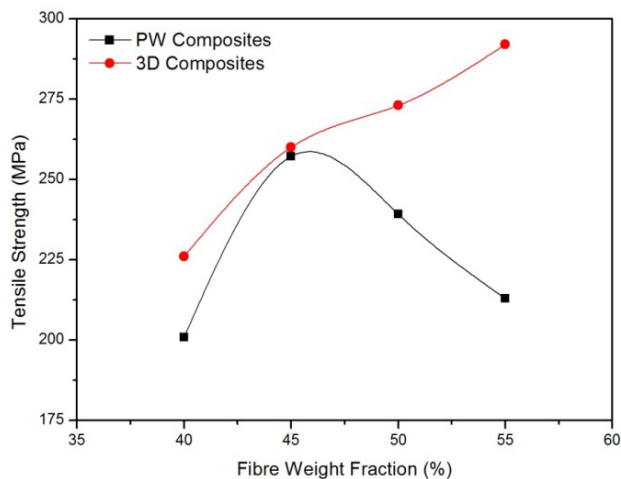


Figure 5. Variation in tensile strength

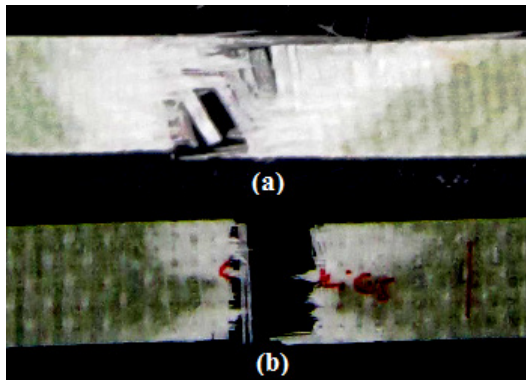


Figure 6. Tensile specimen (a) PW composite; (b) 3D composite

For 3D composites, panel fabricated with 55% FWF gave the best result. Increase in tensile strength with increase in fibre content initially is of the order of 15%. Gradual rise in tensile strength of the order of 5% is seen with increasing fibre content thereafter. Similar behaviour was observed by Siddhartha and Gupta K [3] in their study on properties of chopped and bi-directional E glass reinforced composite materials. Tensile strength of 3D composites in warp direction when compared to PW composites is around 13% more, considering their optimum fibre weight fraction. This is due to more warp ends per cm, straight arrangement of fibres and absence of crimp in the 3D fabric.

In PW composites especially for composites with higher fibre content, higher delamination was seen around the

fracture area representing inner damage and poor interfacial bonding between the constituents. This comparison is presented in Figure 6. Similar findings were reported by Behera B. K and Dash B. P [17] in their study on mechanical behaviour of 3D woven composites.

3.3. Flexural Properties

Flexural test results are shown in Table 3 and Figure 7. PW composite panel fabricated with 45% FWF gave the best results. An increase of 29% in flexural strength is seen with an increase in fibre content from 40% to 45% by weight. Decrease in flexural strength is observed with increase in fibre content beyond 45% by weight. The decrease is drastic when FWF is increased from 45% to 50%. Improper wetting of fibres due to inadequate resin may be the reason for decrease in strength with increase in fibre content. Reduced resin content may have resulted in exposing of brittle glass fibres due to early failure of the matrix leading to early failure of the composites.

Table 3. Flexural test results of PW and 3D composites

Fibre Weight Fraction (%)	Average Flexural Strength (MPa)	
	PW Composite	3D Composite
40	200.56	164.33
45	258.92	261.14
50	175.19	300.25
55	151.24	320.21

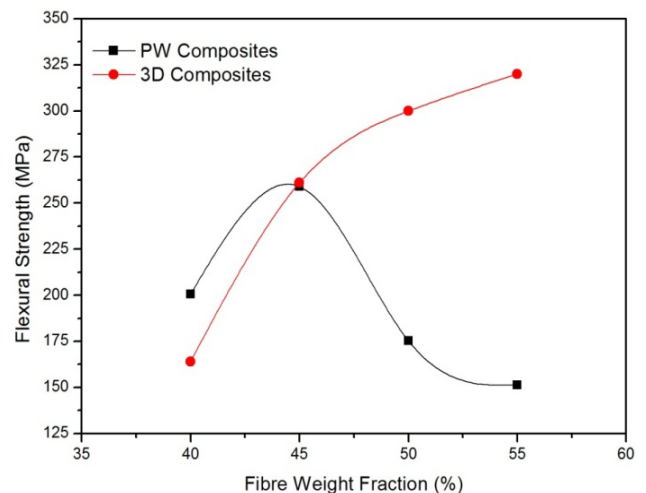


Figure 7. Variation in flexural strength

With 3D composites, it is seen that the flexural strength increases with increase in fibre content. Comparatively 3D composites with 40% fibre content fared poorly than PW composites. This may be due to unsatisfactory wetting, resulting in inefficient transfer of load between the matrix and the fibres. Presence of voids also, may be a cause for the poor performance of 3D composites with 40% fibre content. Highest flexural strength is seen for 3D composites with fibre content of 55%. A steep increase in flexural strength can be seen when fibre content is increased to 50%.

Increase in strength with increase in fibre content is mainly due to better resin infusion associated with single ply of fabric. When optimum fibre content is considered, flexural strength of 3D composites is around 24% more than the PW composites.

The failure in both the types of composites for all fibre content was a combination of tensile failure and delamination. This was evident from cracks that had developed on the outer surface in each specimen. Also the stress developed at failure was comparable with the tensile failure stress values. Opaque zone around the loading region is an indication of delamination. 3D composites suffered lesser delamination as it had comparatively less opaque zones than the PW composites. This can be seen in Figure 8.

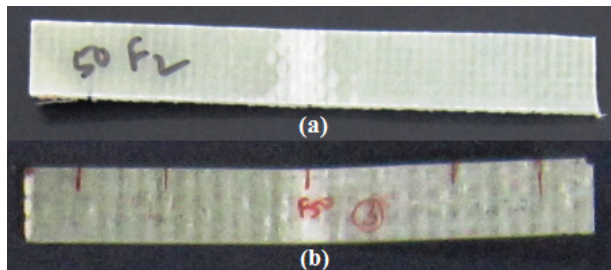


Figure 8. Flexural specimen (a) PW composite; (b) 3D composite

3.4. Inter Laminar Shear Strength (ILSS) Properties

PW composite panel with 45% fibre content was stronger than any other panels when subjected to ILSS tests. The increase and decrease in strength with variation in fibre content were gradual till 50%. Beyond 50% fibre content, a steep drop in strength is seen.

3D composite panel with 55% fibre content showed better resistance to shear loading than the others. The increase in strength with increase in fibre content follows a trend seen in flexural test results. As seen in flexural tests, composites with 40% fibre content exhibited poor strength than PW composites. Inadequate wetting of fibres and presence of more voids could be the reasons for reduced strength. The variation in short beam strength can be seen in Table 4 and Figure 9.

Failure of the specimens was purely inter laminar. Shear strength of 3D composites was around 33% more than the PW composites when optimum fibre content is considered.

Table 4. Inter laminar shear strength test results of PW and 3D composites

Fibre Weight Fraction (%)	Average inter laminar shear strength (MPa)	
	PW Composite	3D Composite
40	22.57	20.35
45	24.96	27.91
50	22.97	31.73
55	17.45	33.36

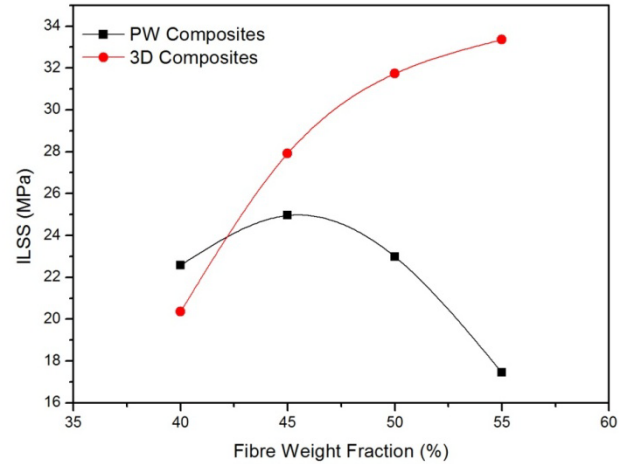


Figure 9. Variation in Inter laminar shear strength

3.5. Impact Properties

Results of impact tests indicate an increase of 15% in energy absorbed when fibre content is increased from 40% to 45%. Like the trend seen from the results of other mechanical tests, with increase in FWF beyond 45%, drop in ability to absorb energy is seen. The drop in impact strength is steep for all the panels with FWF greater than 45%. This may be due to reduced resin content which resulted in exposing of brittle glass fibres due to early failure of the matrix.

Table 5. Impact test results of PW and 3D composites

Fibre Weight Fraction (%)	Average Energy Absorbed (KJ/m ²)	
	PW Composite	3D Composite
40	79.10	110.56
45	92.68	117.89
50	87.40	119.65
55	82.24	121.13

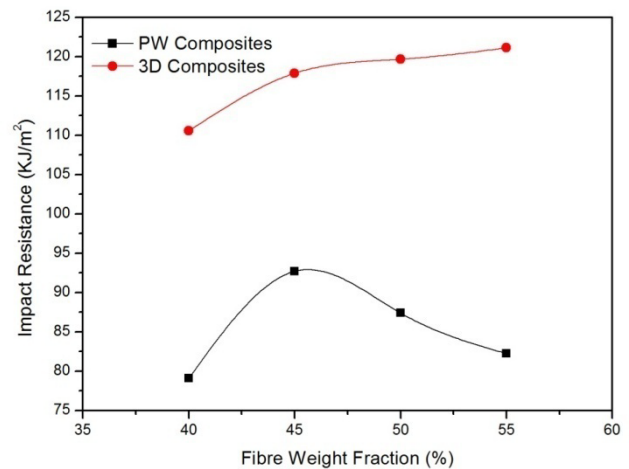


Figure 10. Variation in energy absorbed

Results of impact test on 3D composite specimens' shows an increase in capability to absorb energy with increasing fibre content due to better resin infusion associated with single ply of fabric. Higher stiffness due to reduced interlacing of fibres in 3D fabric increases the ability of the fabric to absorb more energy. Panel with 55% fibre weight content absorbed greater energy when compared to others. Considering optimum fibre content, 3D composites could absorb 30% more energy than PW composites. The results are presented in Table 5 and Figure 10.

4. Conclusions

The following conclusions can be drawn from this study.

- There is an increase in tensile strength, flexural strength, short beam strength and impact strength of PW composites with increase in fibre content from 40% to 45% by weight.
- Optimum fibre weight fraction for PW composites was found to be around 45%.
- With increase in fibre content beyond 45% by weight, a decrease in mechanical properties of PW composites is seen.
- Poor mechanical properties of PW composites at higher fibre content are due to improper fibre-matrix interfacial bonding and poor distribution of fibre in the matrix.
- Sharp decline in properties like impact and flexural strength of PW composites is due to reduced resin content leading to exposure of brittle glass fibres due to early failure of the matrix.
- An increase in tensile strength, flexural strength, short beam strength and impact strength is seen in 3D composites with increase in fibre content
- 3D composites with 55% fibre weight fraction gave the best results among all others.
- 3D composite with 40% fibre weight fraction are weaker than PW composite with same fibre content in bending and shear. This may be due to presence of higher voids and insufficient wetting of the fabric.
- With identical areal densities, composites fabricated with single layer of 3D fabric are stronger than composites with multiple layers of plain weave fabric, due to higher warp ends per cm, absence of crimp and straight arrangement of fibres.

ACKNOWLEDGEMENTS

The authors are thankful to Dr. Divakara Shetty S, Head of the Department, Mechanical and Manufacturing Engineering for permitting us to make use of the Advanced Material Testing and Research Laboratory. The authors are also indebted to Dr. B Satish Shenoy, Head of the Department,

and Dr. Dayanand Pai, Professor, Department of Aeronautical and Automobile Engineering for allowing us to use their Advanced Composite and Material Testing Laboratory. The authors thank Manipal College of Dental Sciences, Manipal for permitting us to use their material testing facilities. The authors are indebted to Mr. Siddaraju, Proprietor, M/s. Mookambika Poly Products, Udipi for helping us during fabrication of the composites. The authors would also like to thank M/s. Konkan Speciality Polypolymers Pvt. Ltd., Mangalore for providing us their testing facility. The authors are also thankful to Dr. Shivamurthy B, Associate Professor, Department of Mechanical Engineering, School of Engineering and IT, Manipal University Dubai Campus for his encouragement to take up this research work.

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