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Influence of textile properties on dynamic mechanical behavior of epoxy composite reinforced with woven sisal fabrics

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Abstract. Due to low cost and environmentally friendly characteristics, natural fibers gain much attention over synthetic fiber. The aim of the present work is to characterize the textile properties of three different types of sisal fabric and study dynamic mechanical properties and water absorption behavior of the sisal fabric reinforced epoxy composite. Influence of grams per square meter of fabric, weaving pattern of the fabric on textile properties of the fabric is studied first. Further, the effect of the same on the dynamic mechanical properties of the sisal composites is studied. Effect of fiber weight percentage and dynamic frequency on dynamic mechanical properties also studied. Results reveal that the storage modulus (G') decreases with increasing temperature in all the woven types of composites under consideration. However, Plain 2 (P2) and Weft Rib (WR) composites have shown better values of G' even after the glass transition temperature (T_g). From the results, it is also evident that storage and loss modulus (G'') increases when the yarn diameter decreases which is observed at a higher temperature also. It is also observed that fabric density also plays a significant role in the enhancement of G' and G'' values. The water absorption of Plain 1 (P1) based composites are found to be less compared to the other types of composites analyzed.

Keywords. Epoxy; woven sisal fabric; warp; weft; dynamic mechanical analysis.

1. Introduction

Over a period of time, the majority of the moderate load-carrying structural member applications in automobiles and other industries are replaced with natural fiber-reinforced composites as they are environmentally friendly [1–3]. In lieu of this, a lot of research work has been accomplished, and these substantial developments have also been made to realize the morphological structures and subsequent properties of these composites [4–6]. However, woven fabric based natural fiber composites have better mechanical properties compared to randomly oriented and nonwoven composites [7]. In this regard, researchers demonstrated that the direction of filler yarn [8], stitched and z-pinned [9], stacking sequence [10] braided composite exhibits better tensile [11], flexural and impact [12] properties. This clearly indicates that the mechanical strength of these woven composites is influenced by natural woven fabric. So, it is important to understand the influence of fabric/textile properties and their effects on composites [13–15].

Behnaz *et al* [12] studied the effect of weave structure on mechanical behavior and moisture absorption of PLA (Polylactic Acid)/hemp woven fabric composite prepared by using compression moulding and observed that satin-weave architecture fabric exhibits the highest tensile, flexural and impact strength. Behera and Dash [16] studied in-plane tensile, compressive, bending, impact resistance, knife penetration and dynamic mechanical analysis (DMA) of unidirectional (UD), two dimensional (2D), three dimensional (3D) orthogonal, 3D angle-interlock and 3D warp interlock multi-layer E-glass composites and observed that 3D woven composite exhibits superior properties. Alcock *et al* [17] studied woven fabric polypropylene [PP] composite and found that its mechanical properties are better as compared to glass fiber reinforced PP. Brandt *et al* [18] observed that woven composites exhibit better in-plane properties, damage tolerance, and energy absorption capacity. Shen *et al* [19] found that tensile strength of 2D CFRP (Carbon Fiber Reinforced Polymer Composite) is 2–2.5 times greater than that of 3D CFRP. Fredrik and Stefan *et al* [20] worked on 3D carbon fiber composite material and found that in-plane stiffness and strength of the composite are lower and out-of-plane properties are higher compared to conventional laminates. Cox *et al* [21]

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demonstrated the failure mechanisms of 3D woven epoxy composites under different loading conditions and found that presence of geometrical flaws that are broadly distributed in strength and space pose great potential for damage tolerance and notch insensitivity.

These literatures suggest using epoxy as matrix material as it played a significant role in the preparation of both natural and synthetic fiber composites. Under temperature and time exposure, polymer matrix composites that are processed under ambient and moderate temperature cure regimes must be studied as the typical application requires a long service life. Dynamic mechanical analysis (DMA) [22] techniques provide a powerful insight into the viscoelastic response of these materials.

Limited research work is reported on the studies on thermo-mechanical properties of 2D natural fiber woven composites. However, no literatures available to understand the influence of sisal textile physical properties under dynamic loading condition. By considering eco-friendliness to its mechanical properties, woven natural fiber composite plays a major role. First, this article focused on the preparation of three varieties of fabrics from sisal fiber, which is available abundantly in India and many parts of the world. Further textile physical characterization of these fabrics. Second, understand the influence of textile physical properties like gram per unit area, yarn diameter, yarn spacing/fabric density, and woven pattern on thermo-mechanical properties of composites. Additionally, to identify the behavior upon fiber loading and its trend for various weight fractions of these fabrics were tested. The water absorption test also conducted to understand the behavior of yarn diameter and twist.

2. Experimental details

2.1 *Materials*

Sisal fibers are used to prepare two types of plain woven fabrics (Plain 1 and 2) and weft rib of woven fabric in OM Textile Industries, Bangalore, India and its properties are shown in table 1 [23, 24]. Figure 1(a) shows the schematic representation of plain and weft rib woven and figure 1(b) shows that woven fabric used to prepare the composites. The difference between plain 1 and plain 2 is grams per square meter (GSM), Plain 1 is denser compared to Plain 2. These basic properties of fabrics are tested as per the textile materials testing standard as given in table 2.

ARALDITE LY 556 unfilled non-modified epoxy resin of low viscosity (5000–8000 mPa s at 20°C) and pot life of ½ to 1 h (at 20°C) were mixed in 10:1 ratio of hardener HY 951 and stirred at 50 rpm using the conventional stirrer to prepare composite. Araldite resin LY 556 with hardener HY 951 is supplied by Zenith Industrial Suppliers, Bangalore, India.

2.2 *Composite fabrication*

Sisal fabric reinforced epoxy composites are prepared by conventional compression molding technique. Woven sisal fabric reinforced epoxy composite prepared by varying (20, 40, and 60%) weight fraction of fiber and matrix materials. The resin mixed with approximately 10:1 ratio of HY 951 hardener for 5 min. The entrapped air bubbles are removed carefully with a roller before the closing of the mould and post-curing is done at 80°C for 4 h followed by after 8 h of room temperature curing.

2.3 *Dynamic mechanical properties of the composite*

The thermo-mechanical responses of the composites are measured using a Dynamic Mechanical Analyzer Perkin Elmer model 8000 instrument in three-point bending mode in a nitrogen environment with a flow rate of 20.0 ml/min. The test is conducted at multi-frequency from 2 Hz to 20 Hz at intervals of 2 Hz linearly with temperature scan from 20 to 160°C with a heating rate of 2°C/min, and a strain of 0.050 mm on rectangular samples with an approximate dimension of 50 × 6 × 3 mm^3. The sample maintained isothermally for 5 min under 3-point bending mode before the starting of multi-frequency mode for better stabilization.

Table 1. Textile properties of the three different fabrics studied.

				Cover factor (%)		Yarn Count in Tex		Yarn crimp (%)		Number of yarns per cm	
Sl. No.	Woven type	Fabric Thickness in mm	GSM	Warp (**P**)	Weft (**T**)	Warp (**P**)	Weft (**T**)	Warp (**P**)	Weft (**T**)	Warp (**P**)	Weft (**T**)
1	Plain 1 (**P1**)	0.42	161.02	79.18	91.78	80.1	85.1	7.23	9.54	18	20
2	Plain 2 (**P2**)	0.73	296.6	74.28	80.24	182.3	166.8	6.53	11.06	12	12
3	Weft rib (**WR**)	0.72	300.45	82.12	53.01	65.3	182.9	10.05	5.96	22	11

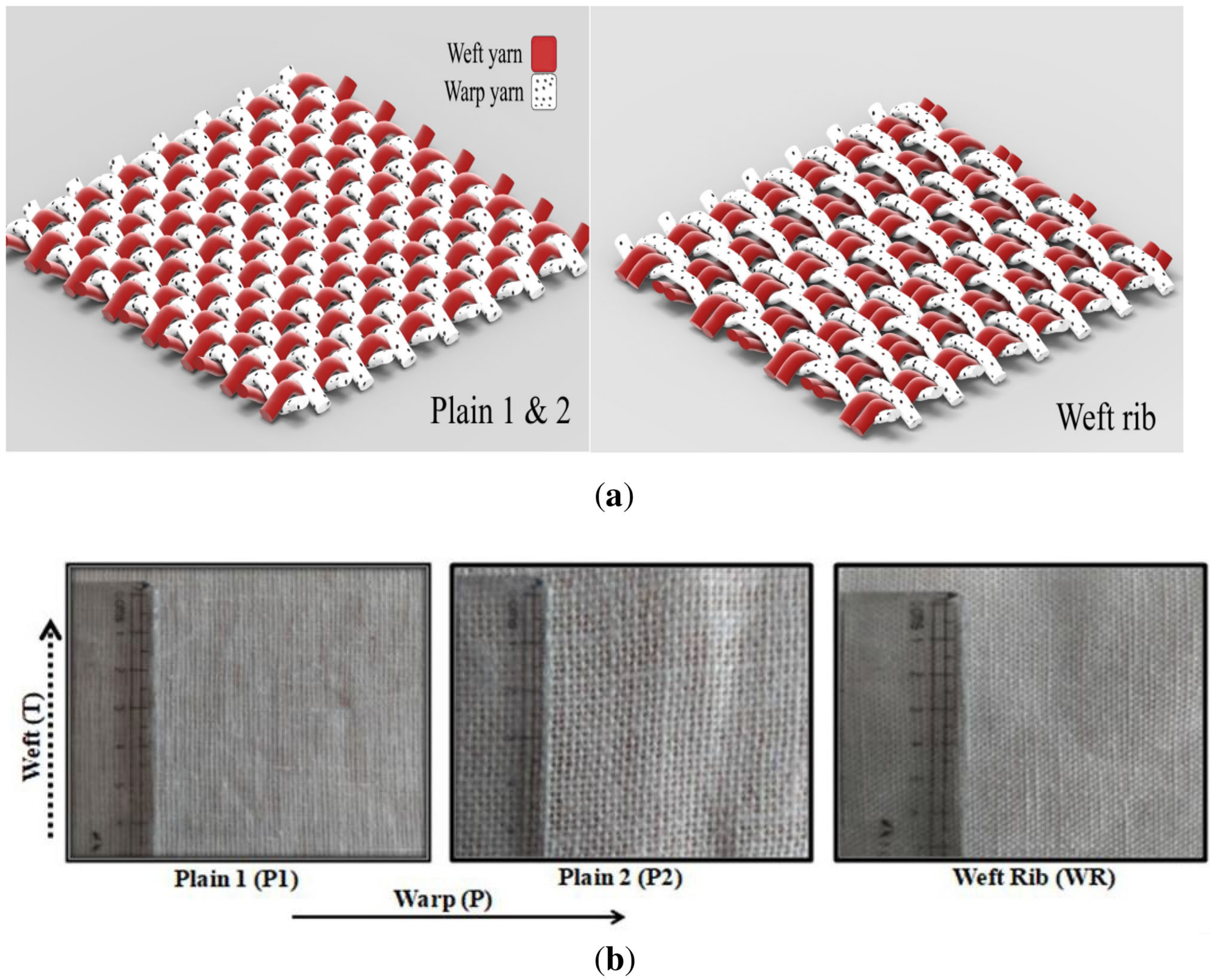

Figure 1. (**a**) Schematic of woven types prepared at OM Textile Industries. (**b**) Three types (two plain and one weft rib) of sisal woven pattern.

Table 2. Different ASTM standards used to determine fabric properties.

Methods	Properties	Testing	Standard method
Yarn testing methods	Yarn crimp	Yarn crimp and yarn take-up in woven fabrics	ASTM: D3883
	Yarn size	Yarn number (linear density)	ASTM: D1907
Fabric basic properties testing methods	Fabric density	Warp (end) and filling (pick) count of woven fabrics	ASTM: D3775
	Fabric weight	Mass per unit area (weight) of fabric	ASTM: D3776
	Fabric thickness	Thickness of textile materials	ASTM: D1777

3. Experimental analysis

DMA is one of the most widely used techniques to evaluate the viscoelastic behavior of polymer composite materials. Among the different types of modes of test, three-point bending is the best appropriate mode to understand the influence of textile properties on the dynamic composites. The complex modulus (E *) of the specimen is composed of an in-phase component G' (or storage modulus) and a G'' (or loss modulus) 90° out-of-phase component. The surface contact between fabric and matrix of the composite material depends on textile properties of the fabric and fiber loading. This in-depth analysis to analyze the effect of textile physical properties on composite over a range of temperature is called as micro-finite element.

The GSM and woven pattern are the two major textile physical properties influences on mechanical properties of composites significantly, the effect of these two properties on thermo-mechanical properties of the composite is analyzed. Effect of GSM is analyzed by considering two fabrics with the same woven pattern (plain 1 and 2). Further, the effect of the woven pattern is analyzed by considering two fabrics with the same GSM (plain 2 and weft rib) but different patterns.

3.1 *Effect of GSM*

P1 and P2 composites are analyzed to understand the effect of GSM on thermo-mechanical properties of the fabric reinforced composites. Effect of weight fraction (W_{ff}) of fabric on storage (G') and loss modulus (G'') of P1 composites is shown in figure 2.

The storage modulus of composites under consideration gradually reduces as the temperature rises. As the temperature increases, the composites undergo a three-phase change that could be described as the glassy region, transition region, and rubbery area. Figure 2 can be divided into three regions: first glassy region (room temperature to 90°C), second transition region (90–135°C), and third rubbery region (above 130°C). The materials are in a frozen phase in the glassy region where the molecules are tightly packed with low mobility resulting in high storage modulus. When sisal fibers are reinforced into epoxy resin, storage modulus a measure of the stiffness of the composite increases with fiber loading [25] at room temperature and even negligible increase above T_g. As illustrated that the storage modulus at 30°C increases by 13% from 0.78 GPa to 0.88 GPa with the addition of 40% P1 weave sisal fabrics which has a mass per unit area of 161.02. The increase in storage modulus could be attributed to an increase in surface area between sisal fiber and epoxy resin [26, 27]. Similar variation in storage modulus is observed for P2 type fabric reinforced composite also as seen in figure 3. The acquired modulus is virtually identical to the flexural modulus through the 3-point bending mode experiment. The flexural modulus is an significant mechanical property used to comprehend material's rigidity [28]. Loss modulus increases by 22%, which suggest that energy is being dissipated at the sisal fabric-epoxy matrix interaction. Since the increase in G' is 13%, while that of G'' is 25%, so the inference is that there is a slip between fiber and matrix phase and there is scope for improving the fiber–matrix interface. Figure 4(d) shows micro-finite element model of P1 based composite, the slip between fiber and matrix interface are due to many reasons (i) the presence resin-rich region between two yarns (X) is higher in P1 based composite, (ii) as thickness of fabric (Y) very less or finer – lesser resistance to flow (molecular movement at higher temperature) it may lead to slip between two plies, (iii) may be very poor bonding between fiber and matrix surfaces. From the above discussion, it is clear that G' and G'' are the function of fiber, matrix and the interface between fiber and matrix.

Figure 3 shows the thermo-mechanical properties of P2 based composites, similar to the P1 composite this graph is also divided into three regions. In case of P2 based composite, G' and G'' values increase by adding 20% with 40% of fiber loading. Thus it can clearly state the energy stored with the addition of fiber and energy dissipated at the sisal fabric matrix interface is more or less equal (energy stored is increased by 23% and energy dissipated is 25%). Due to the softening of the matrix in the composite, the G' reduced with increasing temperature. However, the G' value of the composites improved above the glass transition temperature (T_g) area. The improvement in the G' value even at elevated temperature was found by adding fabric. Figure 3 shows that G' increases at 30°C with fiber loading and also significant change in stiffness value in the rubbery region. Upon comparison of 60% and 20% P2 fabric epoxy composites it was evident that the improvement of G' is maximum and observed to be 1.25 and 3.47 times higher in the

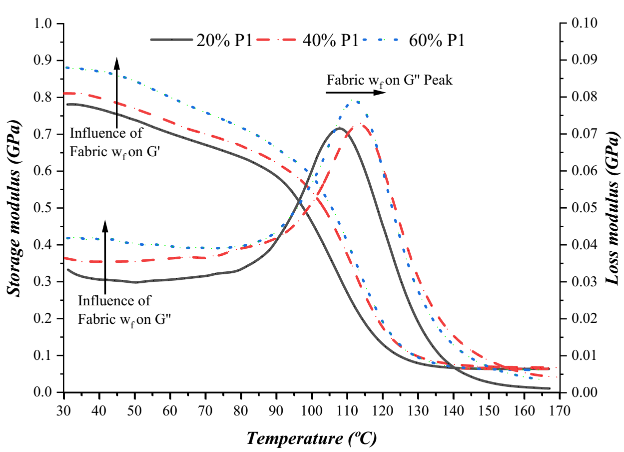

Figure 2. Effect of P1 fiber W_{ff} on dynamic mechanical properties of P1 composite.

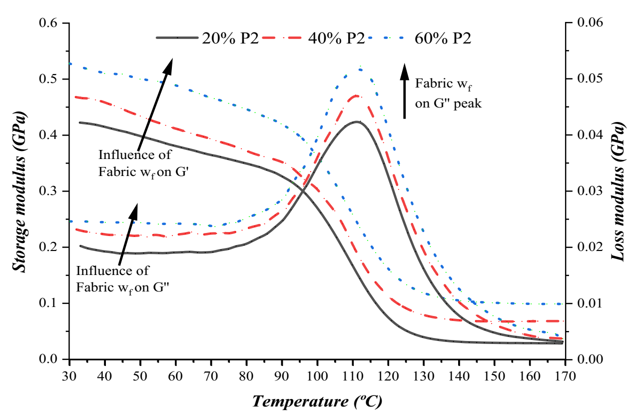

Figure 3. Effect of fiber wt% on dynamic mechanical properties of P2 composite.

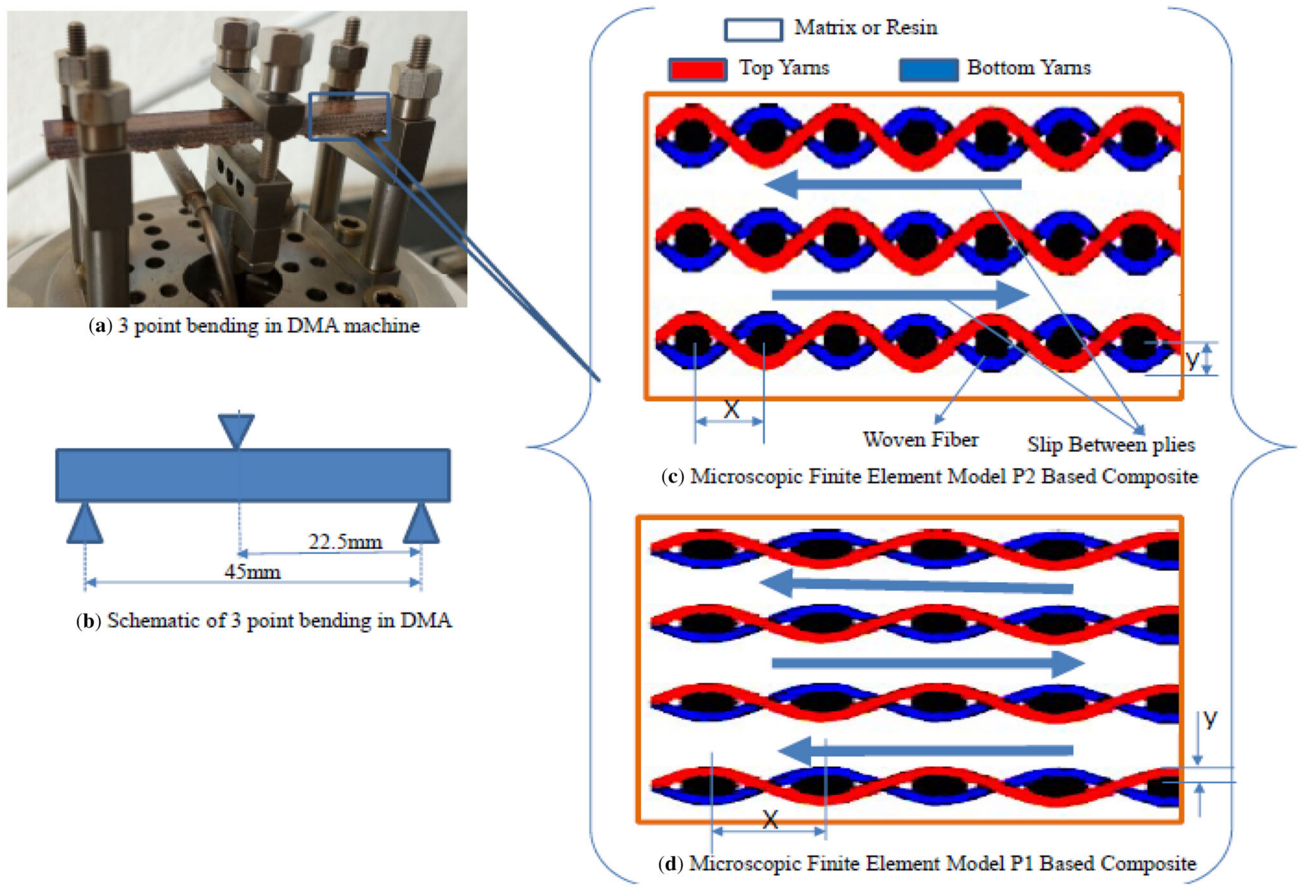

Figure 4. Schematic diagram of micro-finite method analysis of dynamic properties with temperature.

glassy and rubbery region respectively. The enhancement of G′ of the composites in the rubbery region confirmed the good matrix-fiber interaction [29–31].

At higher temperature (rubbery region) the mobility of matrix materials increases, but yarn diameter offers to interlock between two fabric face and offer a resist to the molecular mobility and maintain stiffness even at elevated temperature. However, yarn spacing also affects the dynamic-mechanical properties of the composites. As the yarn spacing increases, the presence of resin rich region and leads to higher mobility at the higher temperature. The G″ is the measure of energy dissipation during sinusoidal deformation during each cycle. The G″ changes are very sensitive to matrix material's molecular motion. The G″ improvement indicates the prominent impact of P2 fabric on the composite's molecular mobility. The incorporation of higher GSM fabric increased the energy dissipation capabilities of the epoxy composites.

$$G' \,\&\, G'' \,\alpha f\,(F, M, I)$$

From the figure 4 micro-finite element model, it clearly shows that,

Where F = fiber region, M = Matrix region, I = Interface between fiber and matrix (bonding).

P1 based composites have better storage and loss modulus compared to P2 composites seen in table 3. This is proportional to the mass per unit area [13] as shown in table 1. The G' of P1 and P2 based composite increased by 12% and 23% by adding 40% fabric loading. This is attributed to lower GSM fabric based composites exhibit

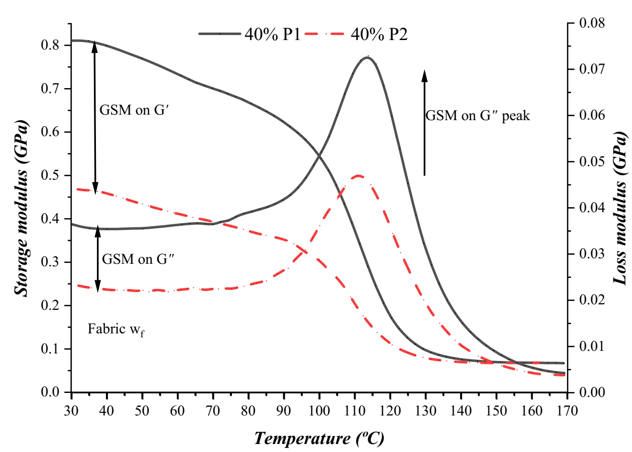

Figure 5. Comparison of DMA results of P1 and P2 composites at 10 Hz for 40 W_{ff}.

Table 3. Effect of GSM on dynamic properties of composites.

Woven type	Weight fraction (W_{ff})	Storage modulus (GPa) at 30°C	Loss modulus (GPa)	
			At 30°C	T_g (°C)
P1	20	0.78	0.033	108
	40	0.81	0.036	114
	60	0.88	0.042	111
P2	20	0.42	0.020	112
	40	0.47	0.023	111
	60	0.52	0.025	112

better properties, but a marginal change in G' value is observed for fabric loading. The G'' of P1 and P2 based composite increased by 27% and 25% by adding 40% fabric loading at room temperature. It also observed that the change in G'' with fabric loading is negligible. It is also observed that the G′ decreases with temperature in both P1 and P2 based composites. In addition to that in the glassy region, the G′ values decrease drastically in P1 based composite as compared to P2 composite. From this, as shown microscopically in figure 5 that in P1 based composite having more slip region than that of P2 based composite. This clearly suggests that sisal fabric GSM has a direct influence on the G′ values and marginal effect on the G″ values. Microscopic analysis and comparative value of G′ and G″ given in table 3 clearly indicate that thermo-mechanical properties are enhanced at room temperature by finer fabric reinforcing. However, these properties are enhanced for higher GSM at elevated temperature. At higher temperature, a substantial reduction of the G′ and G″ values are observed due to the poor fiber–matrix interface in P1 based composite. The glass transition temperature for the P1 based composite shows a shift from 108 to 114°C and which is not as significant as that for P2 based epoxy matrix composites. However, T_g is not influenced by the fiber density, since it is matrix dominated property. The improvement of T_g of the P1 composites is superior to the P2 epoxy composite this is attributed to the addition of finer GSM fabric which enhances the chain stiffness or cross-linking of the matrix material.

Figures 6 and 7 show the variation of G′ and G″ with frequency as a function of temperature for P1 and P2 composites respectively. With the frequency applied, the magnitude of G′ and G″ rises. The frequency has a direct impact on the composites' dynamic modulus, especially at elevated temperatures. The values of the storage modulus start deteriorating at 90–100°C and continued until 130–140°C, depending on the fabric load and the fabric type. The high dynamic modulus of the composites at high frequency is due to the measurements taken for a short period of time [31]. Frequency also had a similar effect on G′ and G″ values as seen from table 4. The T_g increases with temperature as a function of frequency from 105 to 117°C in P1 based composite and 110–117°C in P2 based composites. T_g has always been reported to increase with

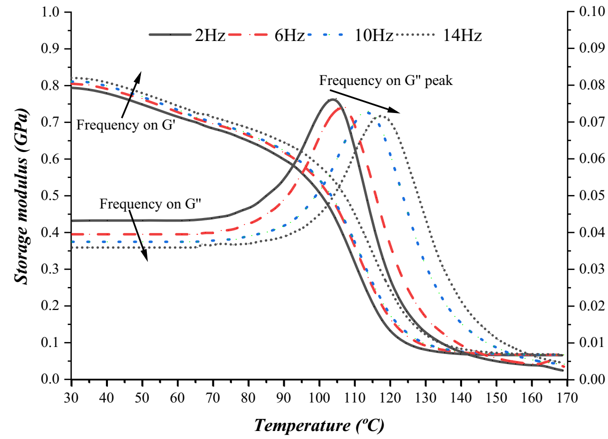

Figure 6. Effect of dynamic loading frequency on P1 based composite (40 W_{ff}).

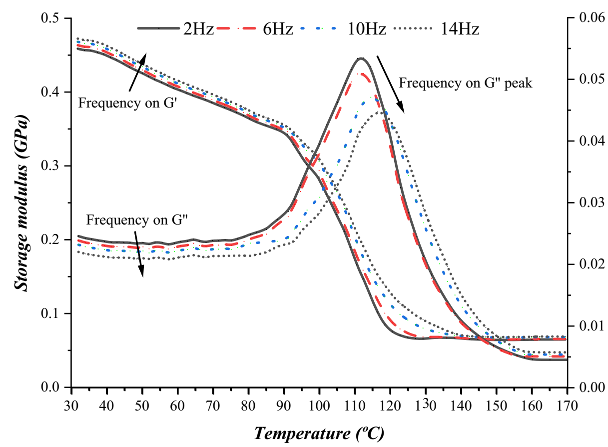

Figure 7. Effect of dynamic loading frequency on P2 based composite (40 W_{ff}).

Table 4. Effect of frequency on dynamic properties of composites.

Woven type	Frequency (Hz)	Storage modulus (GPa) at 30°C	Loss modulus (GPa)	
			At 30°C	T_g (°C)
P1	2	0.79	0.043	105
(W_{ff} 40)	6	0.80	0.039	107
	10	0.81	0.037	114
	14	0.82	0.036	117
P2	2	0.45	0.025	110
(W_{ff} 40)	6	0.46	0.024	112
	10	0.47	0.023	114
	14	0.48	0.022	117

frequency, higher the frequency greater is the T_g, but also the degree of interlocking/cross-linking of the matrix system with fiber based on the geometrical parameters of the fabric system. So, the G″ peak is related to the mobility of the polymeric chain segments.

3.2 *Effect of weave pattern*

WR (Weft Rib) and P2 (Plain 2) composites are analyzed to evaluate the effect of the woven pattern on dynamic mechanical properties of the composite. In WR based composite, the G′ and G″ increase with fiber loading as seen in P1 and P2 based composites. However, G′ increases by 5% and G″ value 28% in WR based composite. From figure 8 it is clearly understood that there is a significant change in G″ compared to the G′. This indicates that woven pattern of the fabric plays a major role in thermo-mechanical properties of a composite. The significant change in G′ with an increase in temperature is observed for WR composites in the rubbery region which is not observed for P1 and P2 composites. This indicates that woven pattern influences dynamic mechanical properties of the fabric composites. This may be due to the presence of one warp yarn and two yarns in weft opposites (resistance) to flow of molecular movements during higher temperature above T_g. The G″ value having more influence on WR based composite below T_g and it clearly showed that energy is being dissipated at the sisal fabric matrix interface. Since G′ increase from 1.63 to 1.70 GPa, while that of G″ increase from 0.07 to 0.09 GPa, it could due to the slip between fiber and matrix phase and there is scope for improving the fiber–matrix interface. The values of thermo-mechanical properties based on fiber, matrix, and interface as explained in micro-finite element model in figure 4.

As compared to P2 based composite, WR based composite G′ and G″ values increased by 3.2 and 3.6 times respectively with the same mass per unit area. This clearly suggests that sisal fiber woven pattern directly influences G′

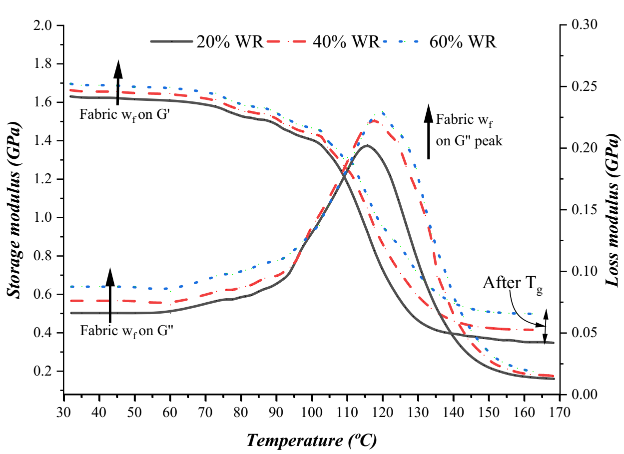

Figure 8. Effect of W_{ff} of fiber on dynamic mechanical properties of WR composite.

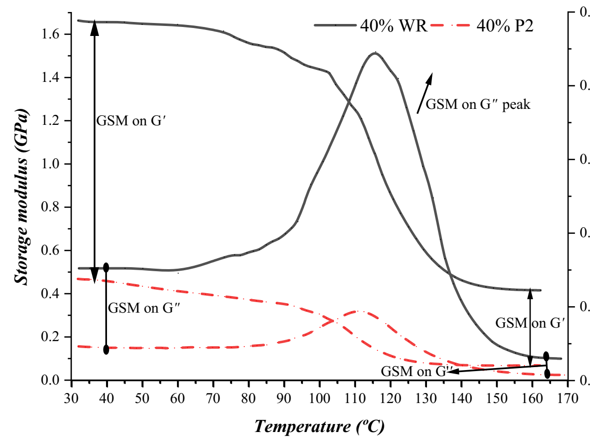

Figure 9. Comparison of dynamic mechanical properties of WR and P2 composite at 10 Hz.

Table 5. Effect of sisal Woven pattern on dynamic properties of composites.

woven type	Weight fraction (W_{ff})	Storage modulus (GPa) at 30°C	Loss modulus (GPa) At 30°C	T_g (°C)
WR	20	1.63	0.07	115
	40	1.66	0.08	117
	60	1.70	0.09	119
P2	20	0.42	0.020	112
	40	0.47	0.023	111
	60	0.52	0.025	112

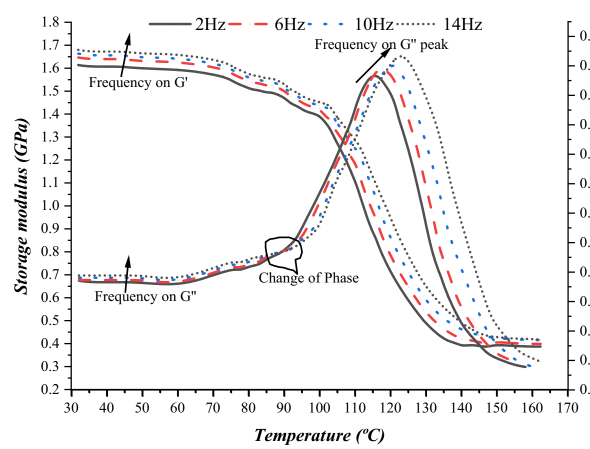

Figure 10. Effect of dynamic loading frequency on dynamic mechanical property of WR composite ($40W_{ff}$).

and G″ of the fabric composite as shown in figure 9 and table 5. However, G′ of P2 and WR based composites increases by 23% and 5% respectively. While G″ values increased by 25% and 28% respectively. This also indicated that woven pattern directly influences on G′ and marginally

Table 6. Effect of loading frequency on dynamic properties of composites.

Woven type	Frequency (Hz)	Storage modulus (GPa) at 30°C	Loss modulus (GPa) At 30°C	T_g (°C)
WR	2	1.61	0.074	115
(W_{ff} 40)	6	1.65	0.075	117
	10	1.66	0.076	121
	14	1.68	0.078	123
P2	2	0.45	0.025	110
(W_{ff} 40)	6	0.46	0.024	112
	10	0.47	0.023	114
	14	0.48	0.022	117

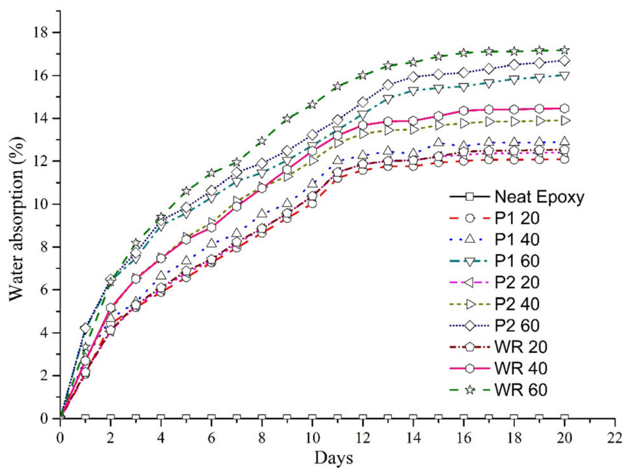

Figure 11. Water absorption of various epoxy reinforced sisal composites at 30°C.

influences on G″ values. As seen in table 5, the T_g value increase from 115 to 119°C for WR based composite, but no significant change in T_g for P2 based composite. Compared to P2 based composite, WR based composite exhibits better performance/properties above T_g. The frequency also had a similar effect on G′ and G″ values as from figure 10 and table 6. The G′ values and T_g values increase as a function of frequency with decreasing G″ values. From the frequency response, it can be clearly observed that as GSM of the fabric increases the change of phase is observed between 95 and 105°C.

3.3 *Water absorption*

The water absorption tests were conducted for neat Epoxy, P1, P2 and WR composites for 20 days with respect to variations in weight fraction of fabric and mass per unit area. Figure 11 shows the percentage of water absorption by various composites at 30°C. The water absorption rate increases up to 14 days, further negligible changes are found in all composites. However, mass per unit area influences on water intake properties. In case of neat epoxy, water absorption is very negligible, by reinforcing sisal fabrics the absorption rate increases. P1 type of composites shows very less water intake percentage, it may be due to the tightness of fabric. In case of P2 and WR the yarn diameter is larger as compared to P1; it allows the flow of water through yarns. As fabric becomes finer the mass per unit area reduces and this in turn contributes to reduced water absorption due to lower water inflow in yarns. It is observed that tighter yarns show lesser water absorption compared to soft yarns this is attributed to twist per unit length, as it is lesser in soft yarns.

3.4 *Micromechanical analysis of woven fabric*

Figure 12 shows a cross-sectional view of P1 based woven fabric and it can be seen that fiber surfaces adhere to matrix face. Due to the cross-linking of two yarns, matrix occupies the gap between yarns, which does not have a significant

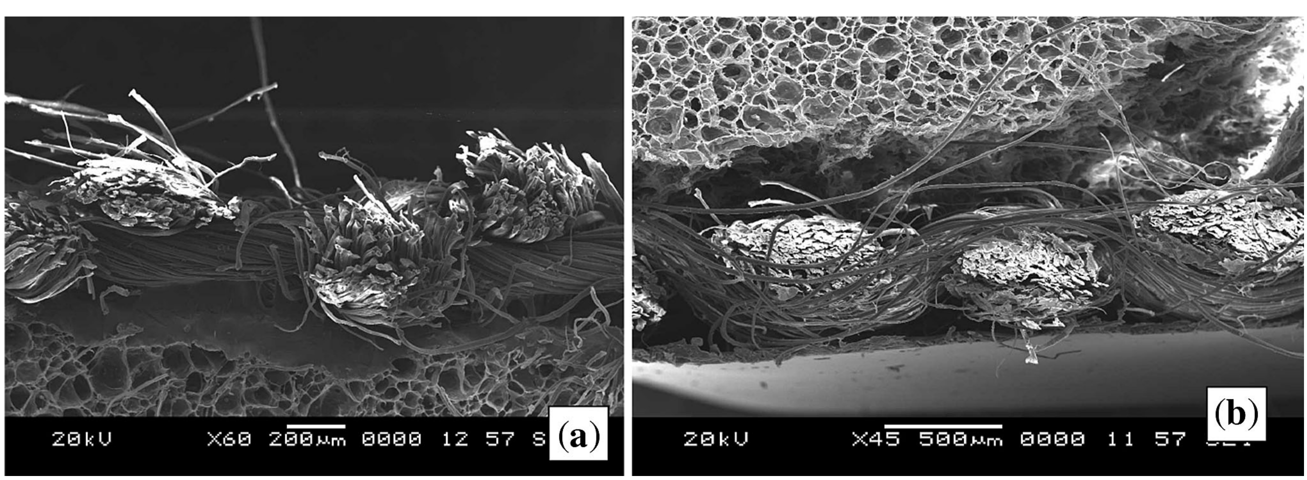

Figure 12. SEM image of P1 (**a**) and P2 (**b**) based fabric cross-section view.

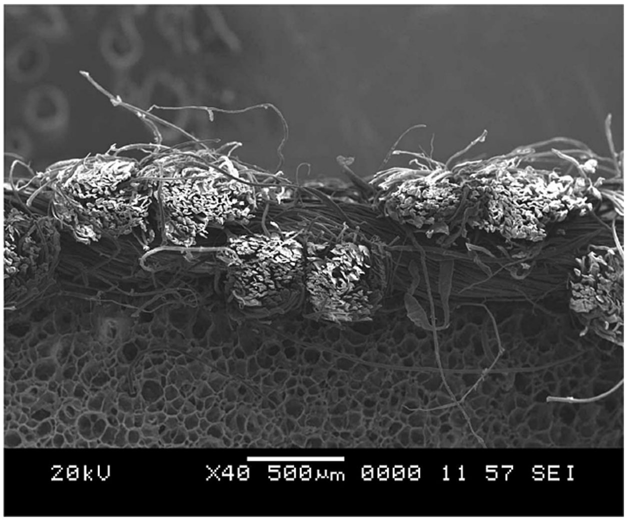

Figure 13. SEM image of WR based fabric cross-section view.

effect at room temperature. However, as temperature increases, molecules start moving with each other. In such case adhesion between fibers to matrix plays a major role and surface geometry also has a significant impact on the molecular movement. It was clearly shown in figure 2 that G′ values are almost equal after T_g up on fiber loading; however, the G′ value in the rubbery plateau region found to increase in P2 based woven fabric with an increase in fiber content, this may be due to the effect of neither fiber diameter nor the mass per unit area of the fabric. This demonstrates improvement in elastic and load-bearing properties in the rubbery region.

The G′ is found to be higher in WR based pattern due to the effect of yarn density in the weft direction as shown in figure 13. In WR based pattern two weft yarns are cross-linked with one warp yarn, it helps to prevent the slip between two laminates by resisting the movement of molecules. This evidenced in that the elastic and load capacity bearing was found to be improved in the rubbery region.

4. Conclusion

The dynamic mechanical properties of the three different fabric reinforced epoxy composites are studied experimentally. Influence of GSM, woven pattern and fabric loading on thermomechanical properties of fabric reinforced composites are analyzed. It is found that the storage modulus and loss modulus increases with increasing in fabric/fiber loading, due to good fabric and matrix interaction in all types of woven fabrics. However even though G′ and G″ increased upon fiber loading, the fabric geometry plays a major role even at elevated temperature.

The thermo-mechanical properties enhanced by finer fabric, as GSM increases the storage and loss modulus are found to decrease. Secondly, as the diameter of the yarn increases the stiffness of composite improved even at elevated temperature observed in the case of P2 woven, due to the increase in the resistance to the mobility of molecules at a higher temperature. Thermo-mechanical properties are also improved by changing the woven pattern as observed in the case of WR composite. Even though WR and P2 woven pattern have the same GSM, the thermo-mechanical properties are improved by 3 to 4 times due to WR fabric. It is also observed that woven pattern also has a significant effect on the dynamic properties of composites. The value of G′ and G″ increased with increasing frequency, as the measurements were taken over a very short period of time. The broadening of the loss modulus curve with increased frequency signified that P2 and WR affected the molecular motions of the epoxy network. The water absorption depended on the yarn twist and fineness of the fabric. The water intake increases due to the softness of the fabric and also because of yarn diameter.

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