Mechanical and Thermo- Mechanical Properties of Woven Sisal Fiber Reinforced Biodegradable Composites

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Abstract— This study mainly focuses on mechanical (tensile and flexural) and dynamic mechanical characterization of fabric reinforced polymer composites. The thesis work is discussed in three phases: matrix, reinforcement, and composites. In the first phase, Polyvinyl Alcohol (PVA) is cross-linked with Glutaraldehyde (GA) for various volume fractions using a conventional vacuum-assisted pressure compression method. The mechanical and dynamic mechanical properties are carried out to optimize the volume fraction and are found at 20%. In the second phase, three types of woven fabrics prepared to study the effect of textile properties and woven patterns. Two plain woven fabrics (Plain 1 and Plain 2) are prepared with different grams per square meter (GSM). Also, another type of weft rib woven is prepared by keeping the same GSM as Plain 2 to analyze the effect of the woven pattern. The mechanical properties of these three fabrics are investigated and found that weft direction of weft rib fabric exhibits better mechanical properties. In the third phase, the composites are prepared using Plain 1, Plain 2 and Weft rib fabrics as reinforcement in 20% GA cross-linked PVA as matrix material and mechanical and dynamic mechanical properties are analyzed.

Keywords- Mechanical Properties, Woven Sisal Fiber, Glutaraldehyde, Polyvinyl Alcohol

I. INTRODUCTION

A composite material system is composed of two or more physically distinct phases whose combination produces aggregate properties that are different from those of its constituents. Composites can be very important because of its strong and stiff, yet very light in weight, so ratios of strength to weight and stiffness to weight are several times stronger than steel or aluminum and also possible to achieve combinations of properties not attainable with metals, ceramics, or polymers alone [1]. In the recent years, natural fibers reinforced composites are treated as most promising material in different application due to its attractive properties (Table 1). Natural fibers are now dominate the automotive, construction and sporting industries by its superior mechanical properties. These natural fibers include flax, hemp, jute, sisal, kenaf, coir and many others [2]. The various advantages of natural fibers are low density, low cost, low energy inputs and comparable mechanical properties and also better elasticity of polymer composites reinforced with natural fibers, especially when modified with crushed fibers, embroidered and 3-D weaved fibers. Glass Fiber Reinforced Polymer (GFRP) is a fiber reinforced polymer made of a plastic matrix reinforced by fine fibers of glass. Fiber glass is a lightweight, strong, and robust material used in different industries due to their excellent properties. Although strength properties are somewhat lower than carbon fiber and it is less stiff, the material is typically far less brittle, and the raw materials are much less expensive. Its bulk strength and weight properties are very favourable when compared to metals, and it can be easily formed using moulding processes. Nowadays, natural fibers such as sisal and jute fiber composite materials are replacing the glass and carbon fibers owing to their easy availability and cost. The use of natural fibers is improved remarkably due to the fact that the field of application is improved day by day especially in automotive industries. Nowadays, natural fiber composites have gained increasing interest due to their eco-friendly properties. A lot of work has been done by researchers based on these natural fibers. Natural fibers such as jute, sisal, silk and coir are inexpensive, abundant and renewable, lightweight, with low density, high toughness, and biodegradable. Natural fibres such as jute have the potential to be used as a replacement for traditional reinforcement materials in composites for applications which require high strength to weight ratio and further weight reduction.

II. CHARACTERIZATION OF SISAL FIBRICS

This chapter analyses the influence of various physical properties of a fabric on mechanical properties of a textile fabric. Three types of woven fabrics are prepared using hand-weaving process and considered as the reinforcement. Two plain woven (Plain 1 and Plain 2) are prepared with different grams per unit area to analyze the effect of GSM on mechanical properties of the fabric. One WR woven pattern is also prepared by keeping the same GSM and compared with P 2 woven pattern fabric to analyze the effect of nature of woven pattern on mechanical properties of the fabric.. Initially, different physical properties of the fabrics are analyzed. Then the different types of the fabrics are investigated for their tensile, flexural, bursting, stretch and recovery, and tearing characteristics. For comparing purposes, the three sisal woven fabrics will be denoted as Plain 1 (P1), Plain 2 (P2), and Weft Rib (WR).

2.1 Sisal Yarn Characterization

Sisal fiber

The cross sections of single sisal fiber are analyzed using SEM analyzed and shown in Figure 5.1 (a). The chemical composition of extracted sisal fiber which is available in Karnataka, India has 62-76% cellulose, 23-36% hemicellulose, 6-9% lignin, 0.8-1.3% wax and 5-10% moisture. The average diameters of the sisal fiber were found to be varying from 100 to 350 micrometers shows in Figure 1 (a). The sisal fiber available in various parts of India is compared from the literatures. *Khan et al.* (2012) reported that sisal fiber which is available in Bhopal has 65-73% cellulose, 9-11% hemicelluloses, 5-6% lignin, 0.9-1.2% wax and 9-11% moisture. Sreekumar *et al.* (2009) studied the southern part of Indian sisal fiber which is available in Kerala region and found that 100-300μm diameter65-78% cellulose, 10-14% hemicellulose, 9.9% Lignin, 2% Waxes. Figure 1 (b) shows the structure of sisal fiber and its details.

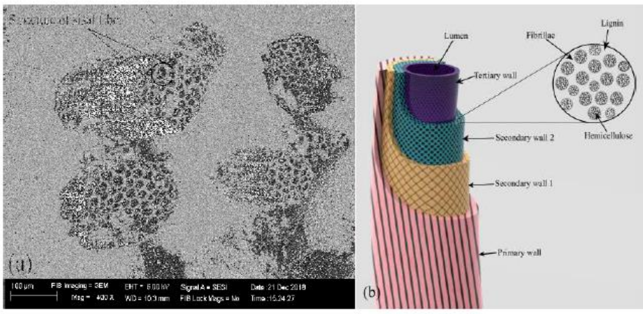

Figure 1: (a) Cross section of sisal fibers (b) Structure of sisal fiber

III. MECHANICAL CHARACTERIZATION OF FABRICS

Tensile strength

The load-elongation curve for the different woven sisal fabrics under tensile loading are depicted in Figure 2 (a). The curve is divided into three phases for the better study of test results. Initial stage of the curve represents the gradual slope and at the end of this stage fabric reaches settlement with linear increase until it reaches the third stage. During the first stage of the curve, elongation increases drastically with a moderate load. This could be attributed to decrimping and crimping interchange and internal crossover between warp and weft yarns of the fabric. The sisal fabric is extended in principal direction and the straightening of crimped yarns is observed in the direction of the applied force. The yarns become less flattened and appear like a compacted into more circular cross-section. The pressure in the yarns along the direction of force is continuously interchanging between two yarns. Consequently this results in the increase in crimp of the yarn along the normal to the direction of force. Further, yarns in the fabric continuously become round and less flattened. Fibre and yarn elongation is occurred at this stage. However, elongation is minimal as compared to the first stage. This little elongation of the yarn is due to the twist, the fiber in tighter and stronger yarn build up pressure and resist tensile force. At this stage, load carrying capacity is found to be maximum and break down of yarn takes place.

From Figure 2 (b) it is noticed that initial portion of curves are raised due to the decrimping and crimping interchange along warp and weft direction. However, this initial slope in the load- extension diagram is due to higher crimp percentage in weft direction (9.54) and lower crimp percentage in warp direction (7.23). This also may be due to the manufacturing effect, as always weft properties are better than warp directions propertiese (Mishra *et al.* 2003). After the decrimping and crimping state at initial stage, the curve rose steeply until the peak (ultimate point) is reached.

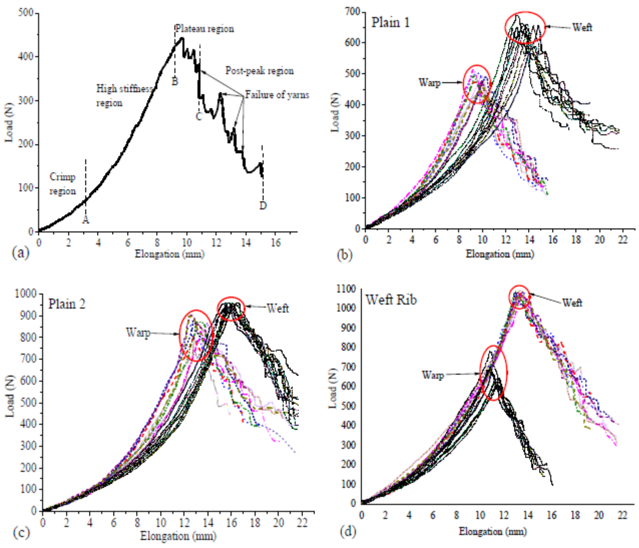

Figure 5.2: (a) Schematic load- elongation plot for fabric and its phases, (b) P 1, (c) P 2 and (d) WR fabrics load-elongation plot for in weft and warp directions

Table I: Tensile properties of fabrics

Type of fabric	Directions	Ultimate Point		Breaking Point		Ultimate Point		Tensile Modulus (N/mm²)
		Load (N)	Elongation (mm)	Load (N)	Elongation (mm)	Stress (N/mm²)	Strain	
Plain 1	Warp	481.2 ±21.5	9.67±0.39	159.72±83.5	14.74±1.28	22.91±1.02	0.048±0.0019	474.743
	Weft	655.9 ±13.1	13.51±0.69	322.53±39.0	20.24±1.55	31.23±0.62	0.068±0.0034	463.237
Plain 2	Warp	869.2 ±31.0	12.88±0.50	405.80±79.3	19.14±2.02	23.81±0.85	0.064±0.0025	370.233
	Weft	952.8 ±8.0	15.85±0.35	471.60±72.8	21.55±0.21	26.10±0.21	0.079±0.0018	329.419
Weft Rib	Warp	672.0±48.2	11.02±0.30	223.40±98.4	14.77±0.96	18.66±1.34	0.055±0.0015	339.405
	Weft	1074.5±10.0	13.21±0.18	421.81±103.3	20.40±1.21	29.84±0.28	0.066±0.0009	451.716

*Note: (±) standard deviation for ten tensile samples

Stiffness strength

Stiffness or bending strength of the fabrics are measured according to ASTM D 1388-96. The flexural rigidity of sisal woven fabric is measured to analyze the effect of selfweight upon overhanging. P1 type of fabric exhibited a flexural rigidity of 2105.1 mg-cm along warp and 545.3 mg-cm along weft direction. It is due to the effect of greater yarn linear density (yarn strength) in weft direction (85.1) compared to weft direction. Higher cover factor along weft direction compared to warp direction which leads to increase in weight of the fabric in weft direction (Table 5.2) and resulted in less flexural strength due to overhanging (self-weight) as seen in Table 5.6. P2 type of plain woven fabric also exhibited flexural behavior similar to P1 type of plain woven fabric. However, flexural strength of WR fabric is less due to less yarn count in warp direction (65.3).

Bursting strength

Bursting strength is the amount of pressure required to rupture a fabric and bursting strength of different fabrics analyzed are given in Table 2. As the bursting strength depends on the cover factor of the fabrics, it is in turn linked to yarn count and yarn density of the fabric. The reinforcement fabrics materials should have good cover factor which permits resin to penetrate into it. However, these bursting properties are linked to tensile and flexural strength, high and low-velocity impacts strengths. So, it is necessary to characterize the fabric materials using bursting tester. Both P1 and P2 fabrics are of plain woven structure but differ by GSM. However, the bursting strength of P1 and P2 are 1.36 MPa and 2.47 MPa respectively. This variation in bursting strength might be due to the fabric weight (P1-161.02 g/m2 and P2-300.45 g/m2), yarn count (P1-80.1 tex and P2-182.3 tex) and cover factor (P1-79.18% and P2-74.28%). P1 type of fabric is thin (yarn count) as compared to P2 fabric and most likely to break at thin places as the fabric possess both thin and thick portions across it. It is noticed that fracture has happened at thin yarn area which is having less yarn coverage area in the fabrics. However, it can be concluded that bursting strength mainly depends on the strength of the yarn and the cover factor.

Table II: Flexural strength, stretch and growth of fabrics

Properties	Directions	Plain 1	Plain 2	Weft Rib
Stiffness strength (mg-cm)	Warp	2105.1	2307	1146.7
	Weft	545.3	771	456.5
Turns per meter	Warp	584	433	436
	Weft	645	425	528
Bursting strength (MPa)	--	1.36	2.47	2.43
Fabric stretch (%)	Warp	0.40	0.8	0.27
	Weft	3.5	1.9	2.6
Fabric growth (%)	Warp	0.17	0.21	0.09
	Weft	1.4	0.9	0.55

IV. TEARING CHARACTERIZATION

Elmendorf tearing properties

Table 3 shows the impact tearing strength of all three fabrics in warp and weft directions. The average impact tearing value of P1 fabric indicates that warp direction exhibit 1.18 times higher resistance than the weft direction. This is due to the higher yarn count of weft yarn along with the higher cover factor. In case of P2 fabric tearing impact strength along warp direction is 1.13 times higher than that of the weft direction. P2 fabric exhibit better tearing strength than P1 fabric, this could be due to the influence of yarn count. The number of yarns is less in P2 (12) as compared to P1 (18). However, the yarn count is higher (182.3 tex) for P2 fabric compared to P1 fabric (85.1 tex). In case of WR fabric, tearing impact strength along warp direction is 1.93 times higher than that of the weft direction. This can be attributed to higher yarn count and cover factor associated with warp direction.

Analysis of variance (ANOVA)

It is very difficult to control the input variable and its effect on the fabric properties due to many limitations. ANOVA analysis is preformed to study the statistically significant parameters that influence Elmendorf tearing properties.

Table III: Impact tearing strength (gram force) of three fabrics

Woven type	Plain 1		Plain 2		Weft rib	
Direction	Warp (P)	Weft (T)	Warp (P)	Weft (T)	Warp (P)	Weft (T)
Trial 1	6656	7168	9728	8704	11392	5888
Trial 2	7552	5376	9600	7936	12032	6144
Trial 3	7296	6272	10112	8320	10368	4992
Trial 4	7424	6528	8704	7808	12288	5760
Trial 5	7936	5888	9472	9216	11008	6784
Average	7372.8	6246.4	9523.2	8396.8	11417.6	5913.6
Standard deviation	466.81	673.67	516.78	576.71	775.43	648.90

The P-value (probability of significance) is then determined from the F-value. The hypothesis assumed as follows: if P-value is equal to or smaller than 0.05 (confidence level 95%) then it suggests that the contribution of the factor is significant. Table 4 shows the variance of impact tearing testing between each group of fabric and Table 5 shows the significance test of fabric between the groups. The P-value of the present analysis is less than 0.05 which indicates that the data is significant. This also indicates that nature of fabric (P1, P2 and WR) and loading direction (warp and weft) influences impact tearing strength significantly.

Table 4: Variance for impact testing of fabric

Groups	*Count*	*Sum*	*Average*	*Variance*
Warp (P1)	5	36864	7372.8	217907.2
Weft (P1)	5	31232	6246.4	453836.8
Warp (P2)	5	47616	9523.2	267059.2
Weft (P2)	5	41984	8396.8	332595.2
Warp (WR)	5	57088	11417.6	601292.8
Weft (WR)	5	29568	5913.6	421068.8

Table 5: ANOVA for impact testing of fabric

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.09E+08	5	21852870	57.16257	1.52E-12	3.89507
Within Groups	9175040	24	38229s3.3			
Total	1.18E+08	29				

V. SINGLE RIP TEAR PROPERTIES

The single rip tearing results of the three different woven fabrics in warp and weft directions are shown from Figure 3 to Figure 4. Figure 3 shows the tearing load carrying capacity of P1 fabric in weft direction at various crosshead speeds of 50, 100, 150 and 200 mm/min. The single tear test described in Figure 5.4 shows each cross section of yarn is subjected to progressively increasing tension. The yarn fails individually in tension and for this reason, the fabric tear strength is much lower than its breaking strength where all the yarns fail at the same time. The mechanism of tearing in woven structures generally includes four main stages: in first stage the stretching and slippage of yarns occurs closest to the tip of the crack; In second stage, the crowding of these yarns on the edges of a Del Zone occurs. In third stage, the stretching and alignment/jamming of these yarns occurs, and in last stage, final rupture of the outer transverse yarn takes place as shown in Figure 4. These stages occur cyclically until the tearing direction reaches the endpoint of loading. A typical tear test load- displacement plot has a saw-tooth shape as shown in Figures 5. The peaks in the load-displacement curve correspond to failure of each successive transverse yarn as the tearing progresses, and the same trend continued till the endpoint of loading i.e., 180 mm. The cross-yarn fails one by one, twice or even in a group of multiple yarns depending on the woven physical properties of the fabric such as yarn strength, elongation of yarn, cover factor, crimp, and woven pattern.

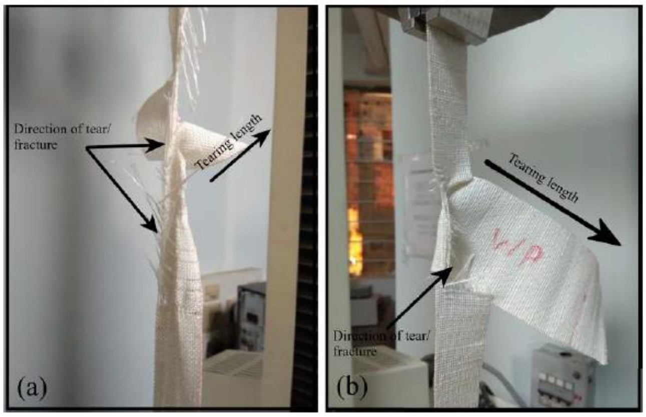

Figure 3: Tearing failure of fabric under single rip tear

Figure 4 and Figure 5 shows the tearing load-displacement curves of P1 fabric in both weft and warp direction respectively. It shows that up to the occurrence of the initial peak resistance against load increases as compared to the remaining tearing length. The increase in resistance against load will occur till the failure of first yarn. This results in stretching of the crack tip which further slip closely to the neighboring yarn and forms Del zone. After this, the crack corresponds to the initial peak propagates and continues along the direction of tearing. The crosshead speed is varied from 50 to 200 mm/min.

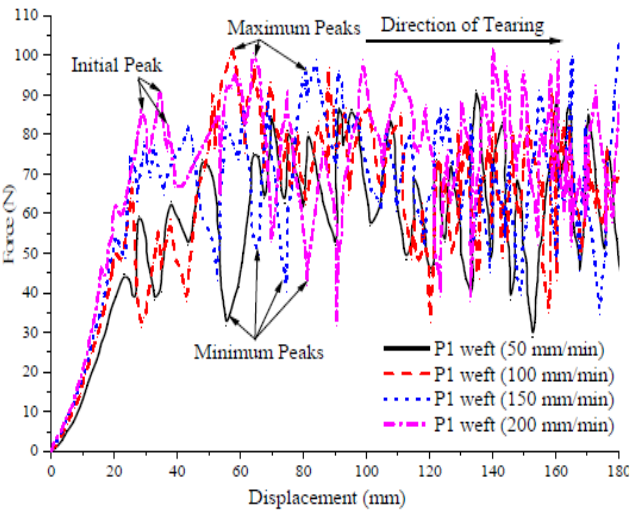

Figure 4: Tearing of P1 fabric in weft direction

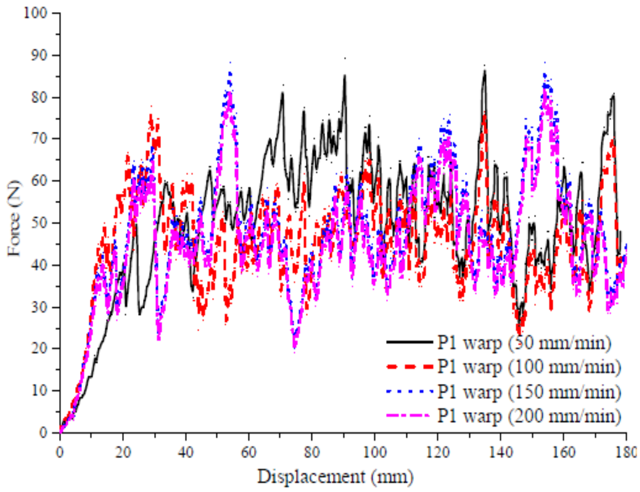

Figure 5: Tearing of P1 fabric in warp direction

VI. CONCLUSION

To summarize the results from this chapter, the influence of textile physical properties on mechanical properties and the deployment of prepared textiles into composite are discussed. It is observed that many of the results are very important in the prediction and interpretation of the properties of sisal fabric reinforced composites.

- P1 type of fabric having fabric density 18 X 20 and yarn count of 80.1 and 85.1 in warp and weft direction, This influenced in the variation of mechanical properties in both warp and weft direction. However, the weft directions possessed the highest tensile properties than the warp direction.
- P2 type fabric possessed similar fabric density in warp and weft direction (12 X 12), even though the tensile properties improved in weft direction.
- WR type of fabric having fabric density (11 warp and 22 weft direction) and yarn count of 65.3 in warp and 182.9 in weft direction and exhibited better tensile properties in weft direction. This clearly concluded that fabric density and yarn count influenced on textile tensile properties.
- Both P2 and WR having same grams per unit area, but different in textile mechanical properties clearly shown that woven structure also influenced.
- The fabric crimp influenced fabric stretch and recovery behavior, higher the crimp percentages better the fabric stretch and recovery.
- The tearing load of the fabric influenced by woven pattern and GSM of the fabric, but yarn crimp, number of yarns and cover factor influenced on tearing length and cyclic behavior of the tear.

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