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Tensile and Flexural Behavior of Sisal Fabric/Polyester Textile Composites Prepared by Resin Transfer Molding Technique

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ABSTRACT: Composites of woven sisal in polyester matrix using three different weave architectures: (plain, twill, and matt) were prepared using a resin transfer molding technique with special reference to the effect of resin viscosity, applied pressure, weave architecture, and fiber surface modification. More than the applied pressure, the resin viscosity, and fiber surface modification, the weave architecture was found to have maximum influence on the ultimate composite properties. The resin permeability, which is related to fiber wetting, was found to be dependent on the weave architecture and the fiber surface morphology. Sisal fibers in woven form, with a fiber volume of 32%, were found to improve the properties of polyester tremendously, irrespective of the resin used and the injection pressure. The maximum improvement in tensile strength was observed for resin with a viscosity of 420 cps. While the tensile strength showed a 32% improvement, the tensile modulus showed a 100% improvement by reinforcing fabrics with the weave architecture with maximum fibers in the loading direction, for the same resin. The flexural strength gave an improvement of 19% while the flexural modulus gave a 55% improvement. Fabrics with maximum fibers in the loading direction (matt weave) proved to be the best reinforcement to impart maximum properties. Finally, the fracture surfaces were examined by scanning electron microscopy to get an insight into fiber/matrix interactions.

KEY WORDS: composites, sisal fibers, resin transfer molding.

INTRODUCTION

CURRENT ENVIRONMENTAL AWARENESS is triggering a paradigm shift towards the use of cellulose fibers as reinforcement in various polymeric matrices. Different cellulose

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fibers have been studied by various researchers all over the world as reinforcement in various matrices. Cellulose content and micro fibrillar angle have been found to be the important parameters, which determine the effectiveness of these fibers as reinforcement in various matrices [1]. Sisal fiber obtained from the leaf of the sisal plant (*Agave sisalana*) has been proved to be a good reinforcement in various polymeric matrices [2].

Textile structural composites are finding use in various high performance applications recently [3,4]. The increased interest in textile reinforcements is due to the enhanced through-the-thickness strength, lower production cost, and improved mechanical properties, which they offer, compared to their non-woven counterparts. Additionally, textile structural composites are associated with near net shape and the cost effective manufacturing process. Another special feature of the textile reinforcement is the interconnectivity between adjacent fibers. This interconnectivity provides additional interface strength to supplement the relatively weak fiber/resin interface. In addition, woven fabric composites may be more damage tolerant in the case of a delamination. Formation of different textile performs is an important stage in composite technology.

The process of weaving in which the fabric is formed by interlacing warp and fill strands/yarns forms woven fabrics. Lateral cohesion is also an important issue to be addressed in the preparation of the reinforcing elements and woven reinforcements are a possible solution. Twisted yarns have been reported to increase lateral cohesion of the filaments as well as to improve the ease of handling [5]. However, by twisting yarns, possible micro damages within the yarn can be localized, leading to possible decrease in the failure strength of the yarn. Whatever the fiber material, fiber architecture has been found to influence the composite properties based on the morphological and structural parameters [6].

Even though reports on the usage of natural fiber as reinforcement in various matrices are there in the literature, usage of natural fiber in the woven form is rare. Bledzki and Zhang has reported on the usage of jute fabrics as reinforcement for the preparation of composites [7]. Since natural fibers are not available in the long form, twisting natural fibers is one way of obtaining these fibers. In fact, fiber twist induces normal forces between fibers and increasing inter-fiber friction gives yarn cohesion.

Manufacturing methods frequently used for natural fiber thermoset composites are modified lay up/press molding, pultrusion, etc. The resin-transfer molding (RTM) process has been used to produce high performance polymer composites. Research in this area has been in progress for many years [8]. Recently RTM has been adopted as a manufacturing process for automotive structural components [9]. Resin impregnation is influenced by several factors such as chemo-rheological properties of the liquid resin, orientation or anisotropy of the fibrous preform, mold temperature, resin impregnation pressure, and surface characteristics between fiber and resin [10]. Oksman et al. has reported on the longitudinal stiffness and strength of unidirectional sisal–epoxy composites manufactured by the RTM process [11]. A detailed review by Mai et al. on the effectiveness of sisal fibers in thermoplastic and thermosetting matrices suggests the usage of the RTM technique for the preparation of composites [12]. Sisal–textile-reinforced composite is an important area in which little work has been done [13]. Rouison et al. [14] carried out cure simulation of natural fiber reinforced composites. In this work hemp/kenaf fiber-unsaturated polyester composites were manufactured using a RTM process. The fiber mats, with a moisture content of 4.3% at 50% relative humidity, were dried in the mold under vacuum to reach a moisture content around 1–2%. RTM composites with various fiber contents, up to 20.6% by volume, were manufactured. The wetting of the fibers was very good. The resin injection time was observed to increase dramatically at high fiber contents due to the low permeability of the mat. Keeping a constant mold temperature is the key to obtain fast and homogeneous curing of the part. The cure of the resin in the mold was simulated and was shown to be in good agreement with experimental results obtained by thermal measurements at different positions in the cavity. Anderson and Sparnins [15] prepared flax fiber composites by resin transfer molding while flax fiber mat/vinyl ester and modified acrylic resin composites are manufactured by resin transfer molding. Behzad and Sain carried out finite element modeling of polymer curing in natural fiber reinforced composites [16]. Plant-based fibers have been selected as suitable reinforcements for composites due to their good mechanical performances and environmental advantages. This article describes the development of a simulation procedure to predict the temperature profile and the curing behavior of the hemp fiber/thermoset composite during the molding process. The governing equations for the non-linear transient heat transfer and the resin cure kinetics were presented. A general purpose multiphysics finite element package was employed. The procedure was applied to simulate one-dimensional and three-dimensional models. Experiments were carried out to verify the simulated results. Experimental data shows that the simulation procedure is numerically valid and stable, and it can provide reasonably accurate predictions. The numerical simulation was performed for a three-dimensional complex geometry of an automotive part to predict the temperature distribution and the curing behavior of the composite during the molding process.

The objective of the present study is to understand the effect of weave architecture, resin viscosity, chemical modification, and injection pressure on the permeability of sisal fabric and the ultimate mechanical properties of woven sisal fiber reinforced polyester composites prepared by the RTM technique.

MATERIALS AND EXPERIMENTAL

Woven sisal fabrics with three different area densities and weave architecture were chosen for the preparation of composites. The fabrics differed mainly in the distance between the weft yarns. The warp yarns were closest in the weave marked 3 (Figure 1(c)). In weave 1, double strands were used with both the warp and weft yarns at 5 mm distance (Figure 1(a)). In weave 2 (Figure 1(b)), the average distance between two consecutive weft yarns is 3 mm, while in weave 3 it is 1 mm. Details of the fabric used for reinforcement is given in Table 1. Two layers of the fabric-arranged parallel to each other were used as reinforcement in composite preparation. Three grades of isophthalic polyester resins with three different viscosities obtained from local sources, was used as matrix.

Twisted sisal yarns were used both in the warp and the weft directions. In all the weaves, balanced two plied yarns were used. The fabric was hand woven, in association with Khadi Village Industries, Thiruvanathapuram, Kerala, India. Two layers of the fabric arranged parallel to the weft and the warp yarns were used as reinforcement in composite preparation. Three grades of isophthalic polyester resins with three different viscosities were obtained from local sources. The viscosities of the resin used, measured using a Brookefield viscometer were 140, 420, and 490 cps. The curing agents used were methyl ethyl ketone peroxide and cobalt naphthenate; 1% each of MEK peroxide and cobalt naphthenate was added to the resin before fabric impregnation. NaOH used for chemical modification was of commercial grade. Vinyl triethoxy silane as coupling agent was obtained from Sigma Aldrich. The resins used, with viscosity 490, 420, and 140 cps are designated as resin 1, resin 2, and resin 3.

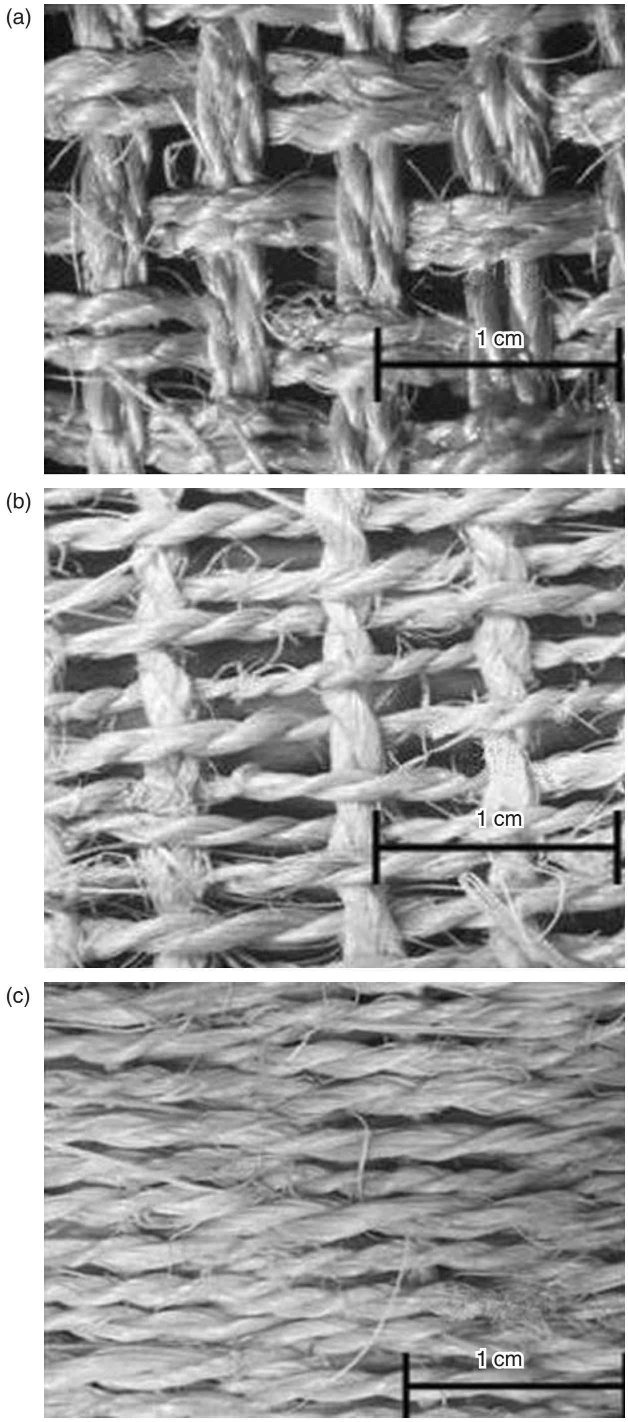

Figure 1. *(a) Plain weave architecture 76 × 61 mm (300 × 300 DPI). (b) Twill weave architecture 80 × 58 mm (300 × 300 DPI). (c) Matt weave architecture 76 × 54 mm (300 × 300 DPI).*

Table 1. Textiles used in the experiment.

Designation	Yarn distance (weft)	Yarn distance (warp)	Twist (turns per mm)	Areal density (g/m^2)
Weave 1	5 mm	5 mm	10	2000
Weave 2	3 mm	5 mm	10	1500
Weave 3	1 mm	10 mm	10	2500

Theoretical Background of Permeability Measurements

Darcy's law governs the one-dimensional flow through a porous medium:

$$u = -\frac{k_{\text{sat}}}{\eta}\frac{\Delta P}{L} \tag{1}$$

where u is the superficial viscosity, k_{sat} the saturated permeability, η the fluid viscosity, P the imposed pressure difference, and L is the flow length. In the case of an advancing flow front where the unsaturated permeability is considered, the capillary pressure also drives the flow. Then Darcy's law should be rewritten as:

$$u = -\frac{k_{\text{unsat}}}{\eta}\frac{\Delta P + P_c}{L}. \tag{2}$$

The capillary pressure on the other hand is inversely related to the hydraulic radius [17]. However, the primary factor influencing the hydraulic radius is the fiber volume fraction. For the same fabric, the higher the volume fraction, the smaller the hydraulic radius and hence greater the capillary pressure.

Permeability Measurements

The permeability measurements were done in a rectangular RTM mold. The mold cavity dimensions were 200×240 mm. The bottom mold was made of mild steel and the top mold was made of 5 mm thick plexiglass so that the flow front progress could be observed visually. The plexiglass mold was reinforced with a grid of steel stiffeners to reduce mold deformation during the test. A grid was drawn on the plexi glass and was used to measure the flow front position.

All permeability tests were carried out at room temperature. The permeability of a single layer fabric was measured in all cases. The fluid was injected into the mold under a predetermined air pressure and the time at which the flow front crosses premarked positions on the plexi glass cover was noted. The gates for resin injection were located at the smaller edge of the rectangular mold. The vent position was arranged on the opposite side. The flow front position at different times was recorded and the volumetric rate of flow of the resin was plotted against the drop in pressure. By measuring the slope of the linear portion of the graph and knowing the relation:

$$K = \frac{\eta L}{A} \tag{3}$$

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where η is the resin viscosity, L is the length of the preform, A is the area of cross-section, and K is the permeability. The permeability was calculated in each case.

CHEMICAL MODIFICATION

Silane Treatment for Sisal Fibers

A 0.6 % of the silane was mixed with an ethanol/water mixture in the ratio 6 : 4, was mixed well and allowed to stand for 1 h. The pH of the solution was carefully controlled to bring about the complete hydrolysis of the silane by the addition of acetic acid. The fabric was dipped in the above solution and was allowed to remain there for 1 ½ h. The ethanol/water mixture was drained out and the fabric was dried in air for ½ h followed by drying in the oven at 70°C until the fabric was fully dry.

Treatment with NaOH

The sisal fabric was dipped in 1% solution of NaOH for 30 min and then washed in very dilute acid to remove excess alkali. Washing was continued until the fibers were alkali free. The fabric was finally washed in distilled water and the washed fibers were then dried in the oven at 70°C for 3 h.

Thermal Treatment

Thermal treatment was carried out by keeping the woven fabric in the oven for 24 h at 70°C. The fabric directly from the oven was used for composite preparation.

MANUFACTURING PROCESS

Composites were manufactured using the RTM processing technique. RTM is a closed mold process where laminates are formed between two stiff mold halves. Two injection gates at the smaller side of the mold, 140 mm apart, were used for injecting the resin. A schematic diagram of the mold used is given in Figure 2.

The pre-weighed fabrics were placed into the mold cavity, the mold was closed and vacuum applied. Degassed polyester resin with curing agents was then injected into the mold cavity. The laminate size was $200 \times 240 \times 6$ mm. Three different pressures, 0.8, 1, and 1.5 bar were used for the preparation of composites. The laminates were allowed to cure in the mold for 4 h and then taken out and post cured. Samples were cut for impact, tensile, and flexural tests starting from the gate regions. The specimens were cut parallel to the weft yarns and a minimum of four samples was tested in each case. The average value is reported. The dart falling impact samples were cut from regions nearest the gate, followed by tensile (marked 1) and flexural (marked 2) samples. Charpy impact samples were cut from areas next to the region from where flexural samples were cut.

MECHANICAL TESTING

Tensile tests were carried out using a universal tensile tester according to ASTM D 638 M using dumb-bell shaped samples (Instron Model 4206). A clip on extensometer

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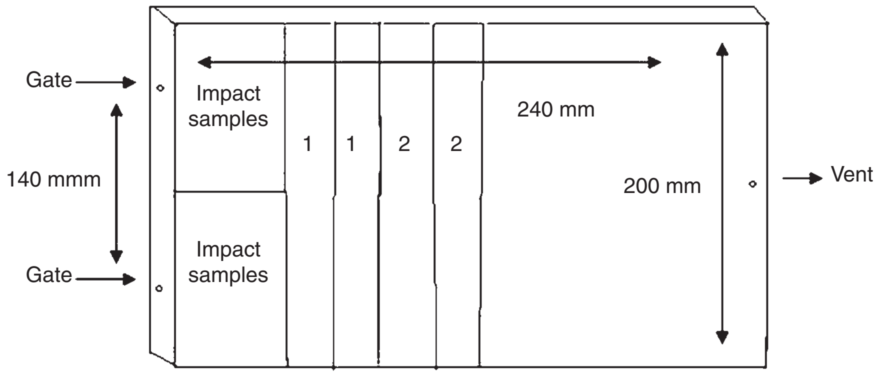

Figure 2. *Schematic diagram of the mold used 166 × 72 mm (300 × 300 DPI).*

with gauge length 50 mm was used to measure the tensile strain to give accurate measurement of the tensile Young's modulus. Flexural strength was determined by testing the samples according to ASTM D 790. Four samples were tested in each case and the average value reported. To have an in-depth idea about the failure behavior of the composites, SEM and optical micrographs of the failed samples were also taken.

RESULTS AND DISCUSSION

Permeability Measurement

The permeability values of the fabrics with the three different weave architectures were measured. It has been reported by other authors that better wetting results in higher measured permeability [18]. In addition to the weave geometry, the effect of chemical modification on the permeability of the fabrics was also noted. Permeability of the resin with viscosity 140 cps, through the three weave architectures were investigated and analyzed. Hammond and Loos had concluded from their studies that the test fluid had no significant influence on the permeability [19]. The relative permeabilities of the three fabrics are shown in Figure 3. Permeability is found to be a maximum for plain weave architecture. In the case of woven fabrics, two types of resin flow occur through the fabric, one between the fiber bundles called the macro flow and the other within the fibers called the micro flow. These in turn are related to the capillary pressure in the fiber bundles. The lower permeability value in the case of matt weave architecture can be related to the greater capillary pressure in the fibers due to the decreased hydraulic radius which result from an increased fiber volume fraction. The increased capillary pressure increases the micro flow through the fibers and these result in a lower macro flow, thereby lowering observed permeability consistent with the observations made by other researchers [20]. In the case of plain weave, the weave pattern leaves a larger interstitial position, which results in an increased macro flow and thereby increased observed permeability. Compared to plain weave, twill weave has more resistance to flow because of the larger number of tows in the fabric, which cause flow resistance.

Figure 4 gives a comparison of the permeabilities of the fabrics after chemical modification. Chemical modification has been found to change the permeability of the fabrics. In addition to the change in the surface morphology, chemical treatment affects the surface polarities of the fibers [21]. Solvatochromic measurements carried out on cellulose

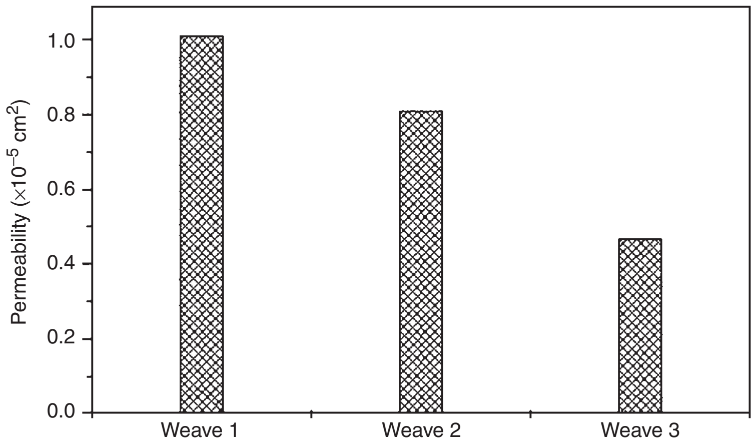

Figure 3. *Relative permeability values of the fabrics with the three different weave architectures 144 × 82 mm (300 × 300 DPI).*

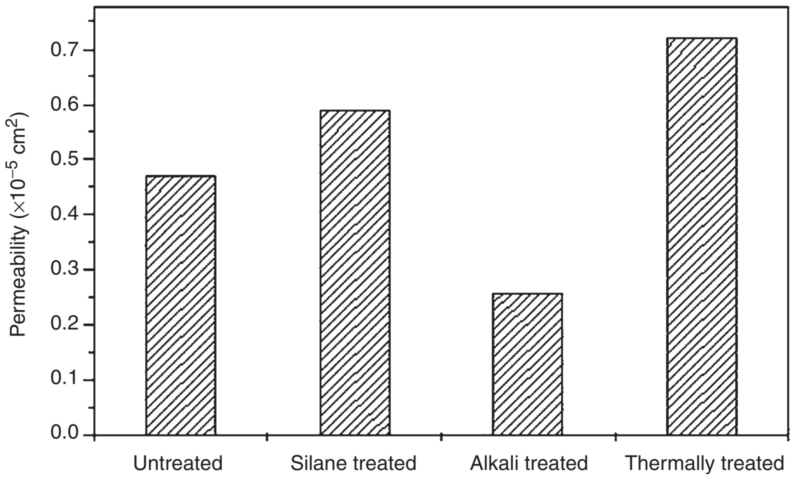

Figure 4. *Comparison of the permeabilities of the fabrics after chemical modification 137 × 86 mm (300 × 300 DPI).*

fibers after chemical modification has shown that surface treatment of the fibers affects the overall polarity of cellulose fibers [22]. Increased polarity improves the wetting and thereby the permeability. Except in the case of the alkali-treated fabrics, the permeability is found to be higher than that of the untreated fabrics. The improved permeability in the case of thermally-treated fabrics can be associated to the escape of moisture from the fabrics which lead to free resin flow through the micro and macro regions. In the case of alkali-treated fibers, more than the polarity and the hydraulic radius, the rough surface morphology leads to a reduction in the flow rate leading to lower permeability values.

Mechanical Properties

Three different weave architectures with area densities 1500, 2000, and 2500 g/m^2 were used for the preparation of composites. Composites with area density, 1500 is marked twill

Table 2. Tensile strength values of the various composites.

Sample	Tensile strength (MPa)	Tensile strength (MPa)	Tensile strength (MPa)	Fiber vol%
	0.8 bar	1 bar	1.5 bar	
Resin 1	29.5 ± 3.6	29.5 ± 3.6	29.5 ± 3.6	0
Weave 1	20 ± 1	16 ± 3.3	19 ± 1	26
Weave 2	25 ± 3	24 ± 0.2	25 ± 6	22
Weave 3	45 ± 5	45 ± 3	54 ± 2	32
Resin 2	40 ± 4.6	40 ± 4.6	40 ± 4.6	0
Weave 1	28 ± 2	21 ± 3	25 ± 2	26
Weave 2	37 ± 3	30 ± 3	30 ± 1	22
Weave 3	53 ± 1.5	56 ± 4.2	50 ± 3.9	32
Resin 3	44 ± 4.7	44 ± 4.7	44 ± 4.7	0
Weave 1	28 ± 5	32 ± 3	29 ± 0.8	26
Weave 2	33 ± 1	37 ± 4	31 ± 2.3	22
Weave 3	67 ± 7	63 ± 2	57 ± 1.6	32

weave, one with area density 2000 as plain weave, and 2500 as matt weave. The tensile properties of the composites were found to be relatively unaffected by the change in pressure for resins.

TENSILE PROPERTIES

The tensile strength values obtained in each case is given in Table 2 with S.D. in brackets.

The tensile strength values of the various composites and the neat resin at a pressure of 0.8 bar is compared and given in Figure 5. The tensile strength is found to be highest for composites with matt weave architecture where the fiber volume fraction is 32% within experimental errors.

While the resin 1 with viscosity 490 cps gave a 55% improvement in tensile strength for the matt weave architecture, it was found to be 32.5% for the resin with viscosity 420 cps, and 52% for resin with viscosity 140 cps. The tensile strength values of composites with plain weave and twill weave architecture was however found to be lower than the neat polyester in all cases. The reason for the lower value in these cases can be explained as due to the fiber volume fraction being lower than the critical value for effective stress transfer. The average fiber volume fraction within experimental errors in the case of plain weave and twill weave are found to be 26% and 22%, respectively. However the values are found to be appreciably higher in the case of composites with the highest volume fraction in the present case namely, 32%.

In the case of woven reinforcements used in the present case, the arrangement of the yarns together with the lower fiber volume fraction gives rise to higher matrix regions. In woven fabric composites, crack originates in the interstitial positions and the lower fiber volume coupled with the weaving arrangement employed presently give rise to more interstitial positions. Orientation of the fibers with respect to the loading axis is an important parameter that determines composite properties. Composite strength and stiffness will be reduced when the fibers are not parallel to the loading direction. In plain weave and twill weave, the number of yarns parallel to the loading direction is lower. In addition, interlace point has been identified as one of the weakest point in most woven fabric composite systems [22]. The interlace points are higher in the case of plain weave

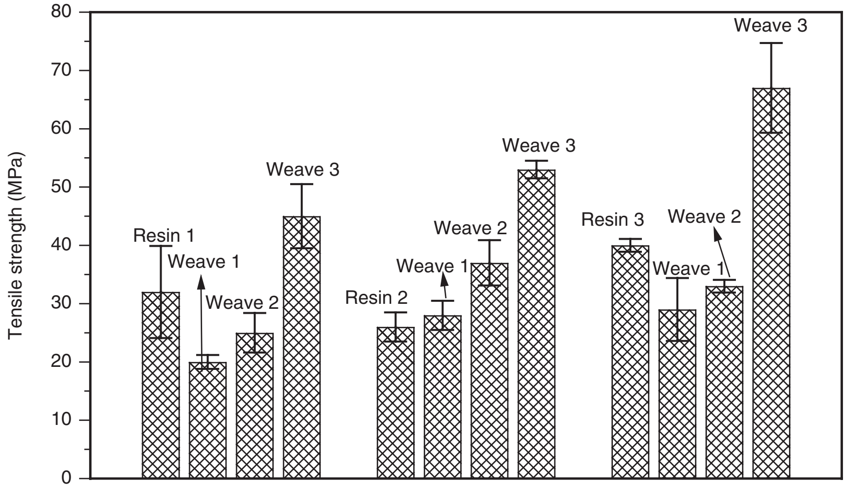

Figure 5. *Comparison of tensile strength values of the various composites and the neat resin at a pressure of 0.8 bar 137 × 88 mm (300 × 300 DPI).*

and twill weave architectures. The interlace points, in addition, has the tendency for more voids and fiber distortion at the interlace gap. These increased interstitial positions serve as crack initiation points. The voids and gaps in the case of composites with plain weave and twill weave architecture are clear from the scanning electron micrographs. The higher value of tensile strength in the case of composites with the matt weave architecture can be attributed to various factors. In the weave geometry adopted in the matt weave architecture, the density of fibers per unit volume is higher. The higher fiber volume fraction helps in crack bridging and crack arresting unlike in the other two cases. This leads to effective stress transfer. In a woven fabric composite, the interlace point has been identified as one of the weakest points. This in turn is dependent on the weave geometry. In the matt weave architecture, the close arrangement of fibers gives rise to lesser interstitial positions and lesser chances of crack initiation compared to the other two weave patterns. From the permeability measurements, it has been revealed that macro flow is comparatively lower in the case of matt weave architecture. In other words, the higher micro flow leads to more penetration of resin in between the fiber bundles.

The tensile moduli of the various composite samples prepared at a pressure of 1.5 bar and using resin 1 is shown in Figure 6. The tensile modulus for composites with matt weave architecture is found to be 6 GPa, while that of the neat polyester is about 3 GPa. The modulus values are found to be improved for the plain weave and twill weave composites as well, even though the tensile strength is found to be lower. The tensile modulus gives a 100% improvement with the incorporation of 32% fiber.

The optical photographs of the cross-sections of the composites with the three weave architectures are shown in Figure 7(a–c), where (a) represents the plain weave, architecture, (b) the twill weave, and (c) the matt weave architecture.

The interstitial regions that serve as crack initiators are clear from the optical photographs. The interstitial regions are more prominent in the case of plain weave and twill weave architectures. The lower strength values in these cases can easily be correlated with the possible crack initiation and propagation due to higher fiber undulation positions in the case of these composites as well as due to the lower fiber volume fraction, which is

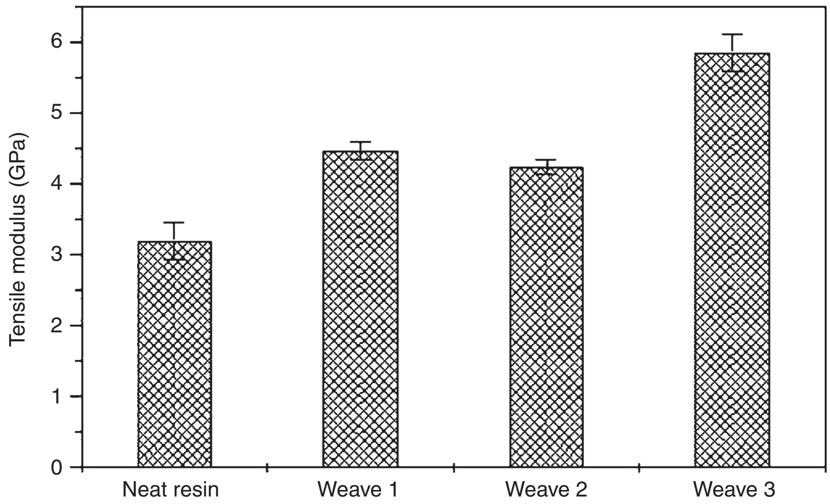

Figure 6. *Tensile moduli of the various composite samples, prepared at a pressure of 1.5 bar and using resin 1 152 × 99 mm (300 × 300 DPI).*

evidently below the critical volume fraction, and hence not enough for effective stress transfer. In addition, composites with lower fiber volume fraction show micro voids, which also explain the lower strength properties.

The tensile stress/strain curve of the composites with three different weave architectures (resin 1 and pressure 0.8 bar) is shown in Figure 8. The tensile stress is found to be maximum for composites with matt weave architecture. The stress–strain curves show progressive failure in the case of composites unlike the neat polyester sample. The progressive failure can be attributed to both shear failure as well as due to the progressive failure of the fabric because of the special fiber arrangement, which gives rise to lateral cohesion. The presence of interlacing gaps in the weft direction relates to the fiber distortion in the region during the molding process. This in turn pushes the 0° fiber to the transverse direction in order to fill up the gaps, and this reduces the composite strength as the percentage of fibers, which are not parallel to the load direction increases [23]. The interlacing gaps are prominent in the case of plain weave and twill weave, unlike matt weave.

FLEXURAL PROPERTIES

The flexural properties of the composites have also been compared. Figure 9 gives the typical flexural load displacement curves for composites with the three weaving architectures prepared using resin 1 and at a pressure of 0.8 bar. The flexural strength is also found to be the maximum for matt weave architecture.

The nature of failure in a composite can be understood from the load deflection curves [24]. The abrupt failure of the composite can be related to flexural failure and when the load deflection curve decreases gradually to zero, shear failure can be assumed to be the predominant mode. A curve between these two forms can be believed to fail by a mixed failure mode. In the present case the nature of the curve reveals a mixed failure mode in the case of composites with all weave architectures. However, the flexural strength is the maximum in the case of composites with matt weave architecture. Figure 10 shows the flexural strength values of the various composites. The flexural strength values show 137% improvement in the case of resin 1 for matt weave architecture, while it is 19% for resin 2.

(a)
(b)
(c)

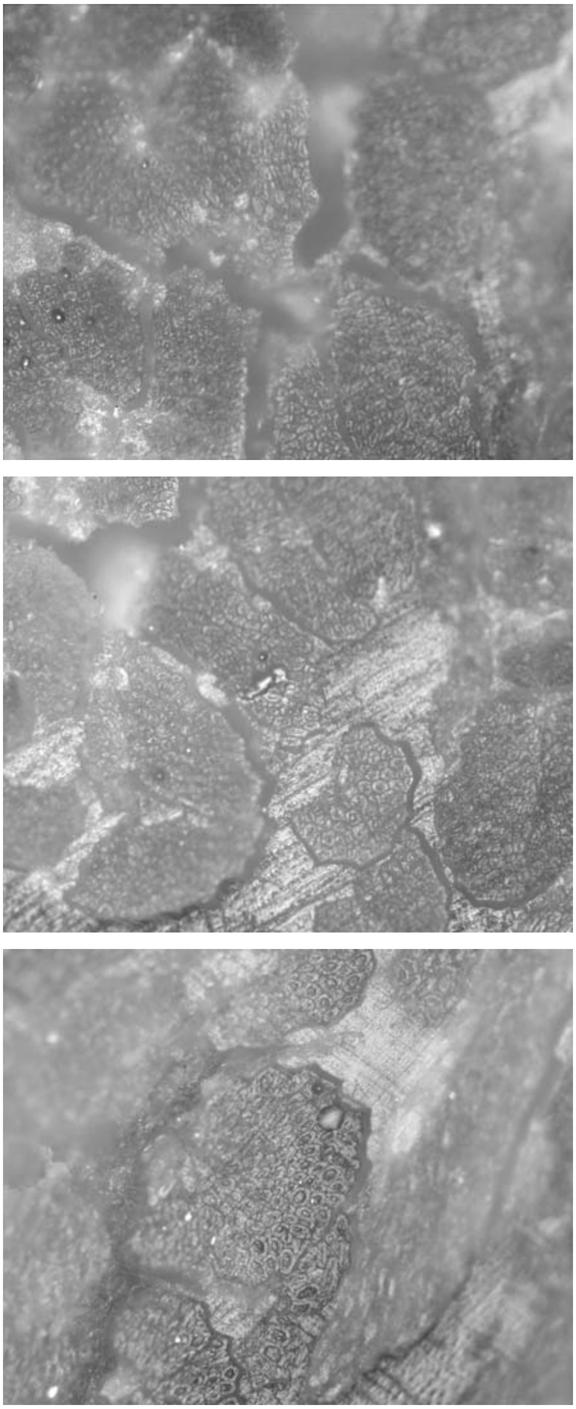

Figure 7. *(a) The optical photographs of the cross-sections of the composites with plain weave architecture 452 × 361 mm (300 × 300 DPI). (b) The optical photographs of the cross-sections of the composites with twill weave architecture 452 × 361 mm (300 × 300 DPI). (c) The optical photographs of the cross-sections of the composites with matt weave architecture 452 × 361 mm (300 × 300 DPI).*

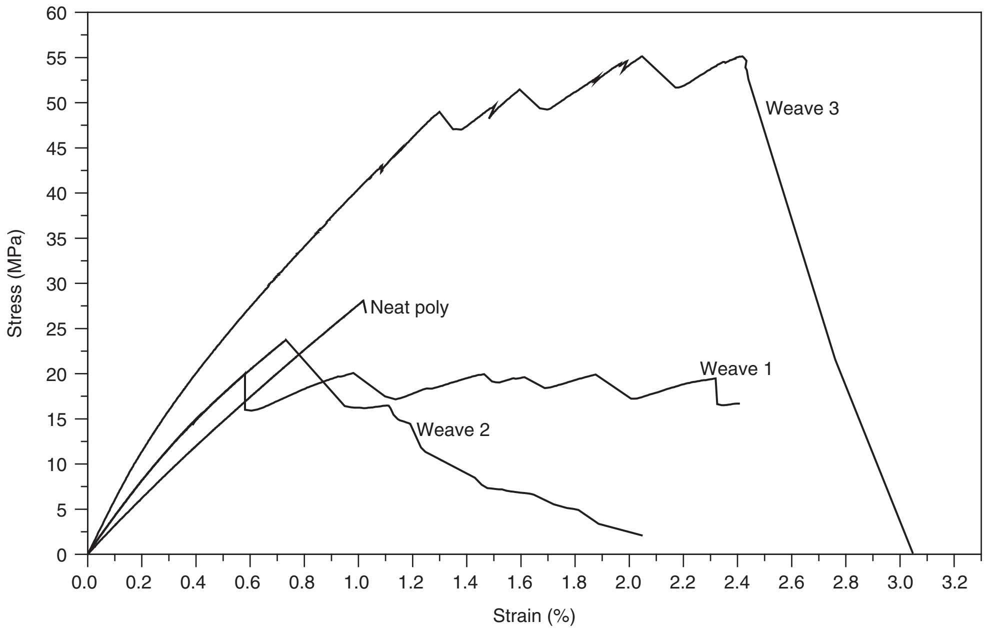

Figure 8. *The tensile stress/strain curve of the composites with three different weave architectures (resin 1 and pressure 0.8 bar) 137 × 96 mm (300 × 300 DPI).*

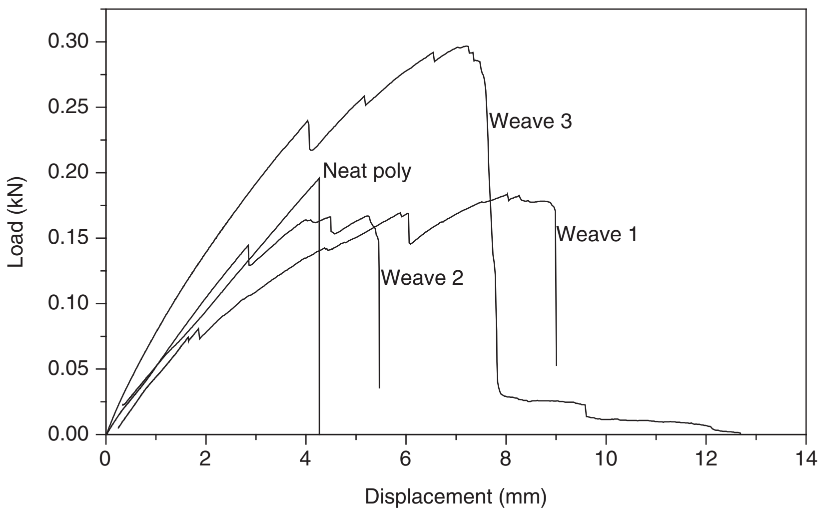

Figure 9. *The typical flexural load displacement curves for composites with the three weaving architectures prepared using resin 1 and at a pressure of 0.8 bar 137 × 88 mm (300 × 300 DPI).*

In the case of resin 3, the improvement is found to be 14%. However, in all the cases, the maximum value is obtained for composites with weave 3 architecture.

FLEXURAL MODULUS

The flexural modulus values for the neat resin with viscosity 420 cps and various composites are shown in Figure 11. The flexural modulus is also highest in the case of the matt weave architecture. The flexural modulus values of the resin and the composites with three weave architectures at an injection pressure of 1 bar are represented in Figure 11. Orientation of the fibers with respect to the loading direction has been found to be a determining factor for composite properties [25]. The fiber orientation in the loading direction is maximum in the case of matt weave architecture and the improved properties in the case of matt weave, compared to plain weave and twill weave can be related to that.

CHEMICAL MODIFICATION

To improve compatibility with polymeric matrices, natural fibers are usually chemically modified using different chemical agents. Reports are there in the literature on the

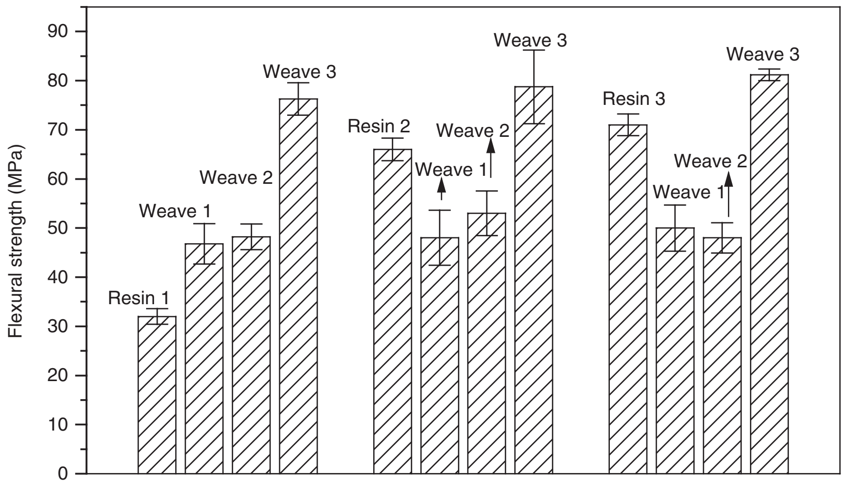

***Figure 10.** The flexural strength values of the various composites 152 × 96 mm (300 × 300 DPI).*

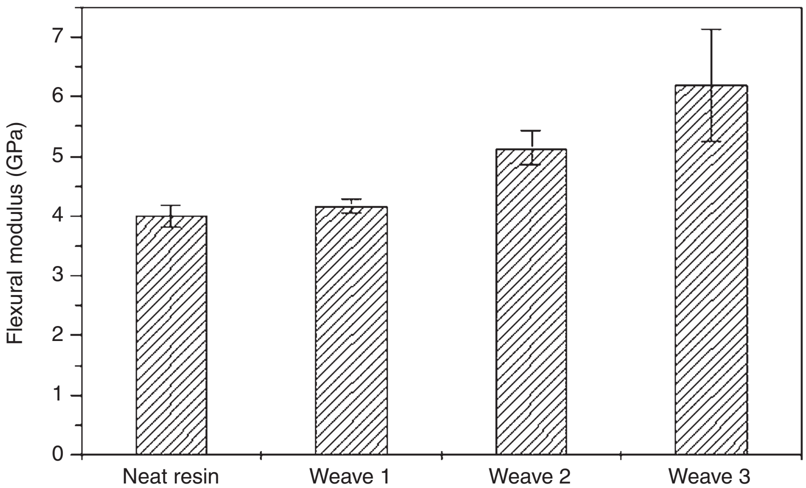

***Figure 11.** The flexural modulus values of the resin and the composites with three weave architectures at an injection pressure of 1 bar 152 × 99 mm (300 × 300 DPI).*

modification of natural fibers using various chemical agents [26]. In the present case three treatments which have been reported to be effective for natural fibers [27] and relatively economical have been tried out to improve fiber/matrix adhesion. The effects of chemical treatment on the tensile and flexural properties of the composites have been compared. The maximum tensile strength is found to be for the composites, which were prepared by chemically untreated fabrics. The tensile strength is found to be lower in the case of alkali treated fiber composites. Other authors have reported on the reduction in the inter fiber differences in orientation by alkali treatment and also a lower critical load for damage initiation with increasing shrinkage state of fibers [28]. Alkali treatment has resulted in the shrinkage and thereby the change in the basic nature of the weave pattern of the composite.

The tensile strength and moduli of the variously treated composites have been studied and are shown in Figure 12. The tensile strength is found to be the maximum for the unmodified fiber composite, compared to the chemically modified fiber composites. Unlike in the case of short fiber composites, where chemical modification has given improvement in properties, the trend seems to be different in the current study. The fabrics were chemically modified after weaving the fibers. One reason that can be suggested for the lowering of properties is the change in the nature of the weave architecture. Twisting of yarns has been reported to lead to a reduction in the ultimate failure strain [4]. In addition to this aspect, the twisted yarns when subjected to various treatments give a further reduction in the ultimate failure strength, the reason for which has to be investigated further.

The SEM of the tensile failure surfaces of the untreated and alkali treated fiber composites is shown in Figure 13(a–c). The long fibers at the fracture surface are seen for the untreated composites, (Figure 13(a)). However, the alkali treated composites show voids in the matrix, which essentially seems to be the reason for the lower strength properties of the composites. Micro voids can form in composites during resin flow due to resin flowing around fiber bundles before it can penetrate. In the case of short fiber composites subjected to alkali treatment, mechanical interlocking due to rough surface morphology had been suggested to be the reason for the improved properties. However in

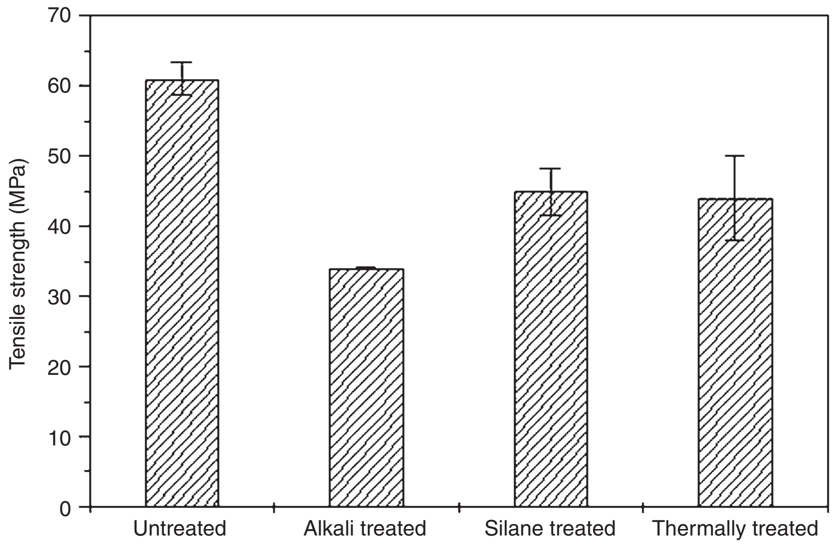

Figure 12. *The tensile strength of the variously treated composites 137 × 96 mm (300 × DPI).*

(a)
(b)
(c)

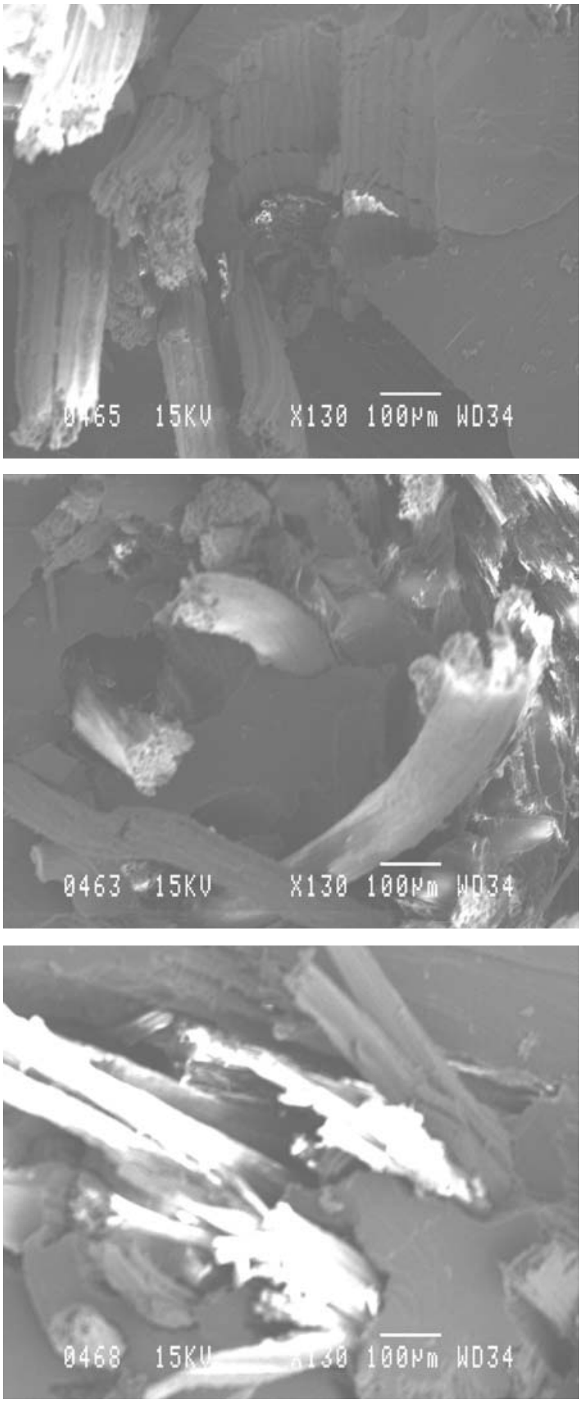

Figure 13. *(a) The SEM of the tensile failure surfaces of the untreated fiber composites 322 × 254 mm (300 × 300 DPI). (b) The SEM of the tensile failure surfaces of the alkali treated fiber composites 322 × 254 mm (300 × 300 DPI). (c) The SEM of the tensile failure surfaces of alkali treated fiber composites 322 × 254 mm (300 × 300 DPI).*

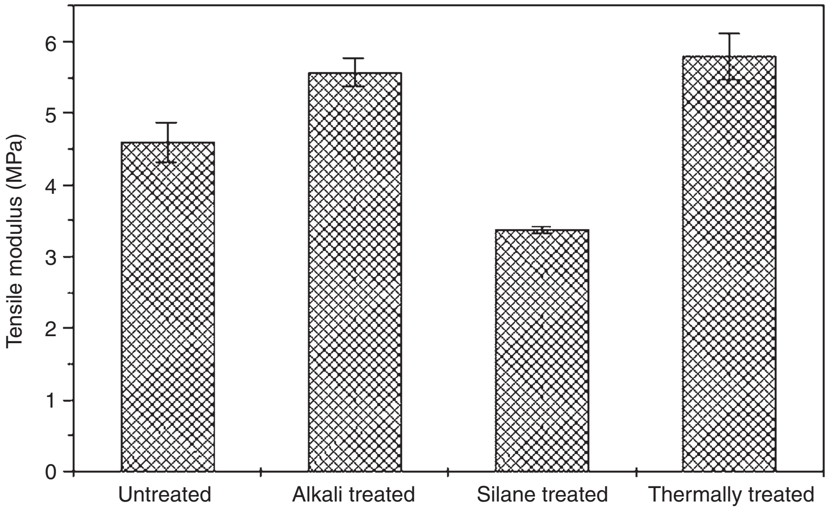

Figure 14. *The tensile moduli of the variously treated and untreated composites 149 × 97 mm (300 × 300 DPI).*

the present case, when the yarns are in the twisted form, lateral cohesion seems to be improved more than the mechanical interlocking. Permeability studies showed a lowered permeability for the alkali treated fibers. The change in the fiber surface morphology is a contributing factor for the reduced permeability and wetting. The rough fiber surface morphology, which results due to the dissolution of the lignin component, restricts the free flow of the resin. In addition, the dissolution of the lignin leaves holes on the fiber surface which results in micro flow rather than macro flow. Other authors have already reported rough fiber surface morphology of alkali-treated fibers.

The tensile moduli of the variously treated and untreated composites are shown in Figure 14. In the current case, resin 3 and fabrics with matt weave architecture has been chosen.

Unlike the tensile strength the tensile modulus seems to be improved in the case of alkali treated fiber composites. The reason for the improvement in modulus can be attributed to the change in the intrinsic structure and thereby the crystallinity of the fibers. Reports on the change in the intrinsic fiber properties on alkali treatment are there in the literature [29].

The flexural strength of the composites with treated and untreated fibers is shown in Figure. 15. The flexural properties also seem to be lowered by chemical modification. But the relative lowering in properties is found to be less than in the case of tensile strength.

The flexural modulus values in the case of the untreated and treated composites are shown in Figure 16. The flexural modulus value is found to be highest for alkali-treated composites The value is slightly low for thermally-treated composites.

CONCLUSION

The effect of fiber-weaving architecture and chemical modification on the resin permeability in the case of woven sisal fabrics was investigated along with the tensile and flexural performance of the prepared composites. The weaving architecture and the fiber content were both found to have an effect on the composite mechanical properties.

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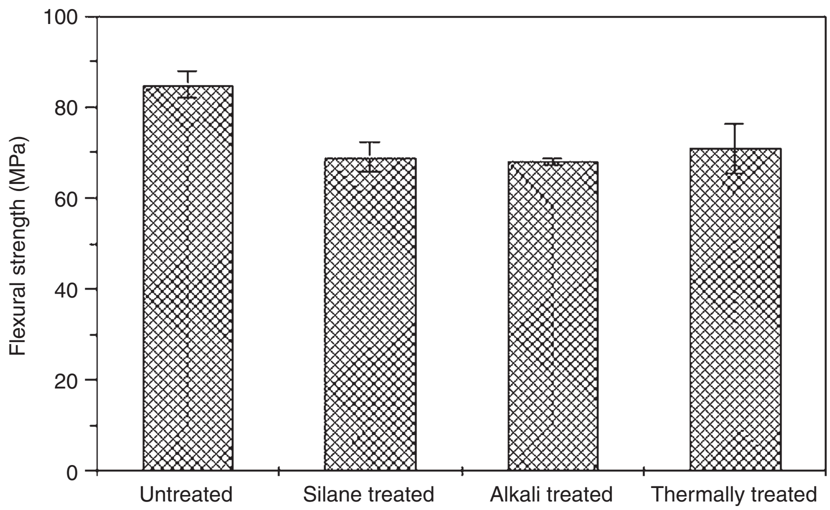

Figure 15. *The flexural strength of the composites with treated and untreated fibers 149 × 97 mm (300 × 300 DPI).*

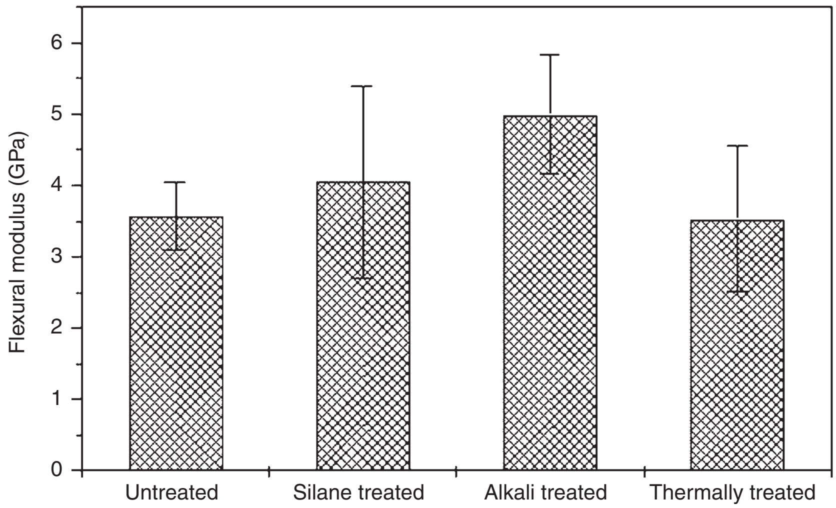

Figure 16. *The flexural modulus values in the case of the untreated and treated Composites 149 × 97 mm (300 × 300 DPI).*

Matt-weave architecture with a fiber content of 32 vol% gave higher tensile and flexural properties. While the tensile strength showed an improvement of 52%, the tensile modulus gave an improvement of 100% in the case of composites with matt-weave architecture. More than the fiber loading, the weave architecture was found to determine the ultimate composite properties. Composites where maximum fibers are in the loading direction, combined with lower interlace points, were found to give highest properties. Irrespective of the resin used and the injection pressure applied, composites with the weave architecture where there are maximum fibers in the loading direction gave the maximum improvement in mechanical properties. In the case of woven reinforcements, fabrics in the chemically unmodified form was found to give better performance compared to the modified ones in the current study. But compared to the short fiber composites, the strength properties seem to be much higher in the case of woven reinforcement with a relatively lower fiber volume fraction. Natural fibers in the woven form have an edge over short-fiber composites of the same material and the weaving architecture seems to be the governing factor which controls the ultimate properties.

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