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Mechanical Behaviour of Hybrid Composites Developed from Textile Waste

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Abstract

The current study focused on the use of textile industry waste (cotton and jute) and glass fabric for the development of hybrid composites. Composites were fabricated using either a single reinforcement or different fractions of cotton, jute and glass fabric. A good fibre-matrix interface was observed using Scanning Electronic Microscopy (SEM). The mechanical performance of the composites developed was analysed under certain loads. The tensile and flexural properties of the composites developed from waste material was found lower as compared to the glass fiber composites, while hybrid composites had comparable properties. Regression equations were also developed to predict the mechanical properties of the hybrid composites. Dynamic Mechanical Analysis (DMA) results revealed that after some pre-treatment (mercerization and desizing) textile waste materials can be used with virgin material in the reinforcement part of the composite to decrease the cost, but with optimum mechanical properties.

Key words: *hybrid composite, textile waste, dynamic mechanical analysis, mechanical properties.*

Introduction

Fiber reinforced composites (FRC) are used for a wide range of applications, from water storage tanks to high tech aircraft parts. The mechanical performance of a FRC is mainly a function of the reinforcing material, i.e. natural or manmade fibers [1]. Glass fibers are the most commonly used reinforcement material, occupying an 87% market share of FRCs [2]. However, the production, usage and disposal of these composite structures (reinforced with glass fibers) is declining due to increased environmental concerns. It motivated researchers to look for alternative materials, and natural fibers appeared as a potential substitute [3]. The advantages offered by natural fibers over glass fiber include sustainability, low cost, ease of availability, low density, biodegradation and low health hazards [4] [5]. Among the various plant based fibers, flax, bamboo, sisal, hemp, ramie, jute, and wood fibers are of particular interest [6]. Animal-based fibers e.g. wool and silk, are also used as reinforcements for FRCs [7]. Silk fiber reinforced composites have been investigated in view of bioengineering applications such as scaffolds for tissue engineering and bone fixators [8]. Current research interest is towards recycling and value addition to low cost materials. With a view to better saving of land, for example, perennial grasses such as Indian-grass or switch-grass were investigated as reinforcing agents [9]. Composite materials reinforced with switch-grass stems were used for automotive interiors, showing higher modulus, flexural strength and impact resistance as compared to jute- PP composite of the same density [10].

Tailored properties in a single piece of composite material may be achieved using more than one reinforcement or matrix [11]. Such composites are termed as hybrid, and can be manufactured by using synthetic fibers, natural fibers or with a combination of both synthetic and natural fibers [12].

Another approach to value addition is the extraction of fibers from agricultural or industrial waste. Attempts have been made to use sunflower stalk, bagasse [13], rice husk, cornhusk [14], wheat straw [15], and soy stalk [16] as sources of cellulosic fibers to serve as reinforcement in FRCs. Cellulose fibers with properties midway between those of cotton and flax were successfully extracted from cornhusk, a by-product of corn production that is worldwide available and has limited commercial value [17]. This approach also contributes to solving the problem of agricultural waste disposal [18].

Other potential waste fiber sources include animal-derived protein wastes, such as by-products from the wool textile industry (poor quality raw wools not suitable for spinning), hair, and feathers. The hollow structure of keratin fibers leads to an extremely low fiber density that can be used to obtain light-weight materials for automotive applications [19]. Overall the use of fibers from waste (either agricultural or animal) as reinforcement in bio-composites offers a low cost and environmentally friendly solution to waste disposal [20].

However, lack of good interfacial adhesion, susceptibility to bacterial attacks and poor resistance towards moisture make the use of natural fiber reinforced composites less attractive [21]. Pretreatments (mercerization, scouring, etc.) of the natural fiber clean the fiber surface and chemically modify the surface to reduce moisture absorption and enhance surface roughness [22]. The bacterial attacks may be avoided by the addition of some fillers with antibacterial activity [23].

Generally 16-17% of cotton fibers are wasted due to their short length, which makes them unsuitable for making fine and high strength yarn. The price of finished yarn is increased due to this 17% waste [24, 25]. However, these waste fibers can be used for making low strength yarn that can be used for making composite reinforcement [26]. But the mechanical performance of these composites is lower than that of glass fiber composites [27]. This problem can be overcome by using waste fibre reinforcement along with virgin reinforcement, thereby producing a hybrid composite, which will be of low cost.

The aim of this study was to minimise the use of synthetic fibers by developing hybrid composites reinforced by waste natural fibers (textile industry waste) and virgin synthetic fibers and to find the best combination of waste and virgin fiber based reinforcement with optimum mechanical properties. This study also increased the value of textile waste and maintained environment hygiene by minimising waste.

Materials and methods

Three types of yarn were used to fabricate reinforcement for the manufacturing of composite structures i.e. cotton, jute, and glass. The areal density of woven cotton, jute and glass fabric was 200, 270 and 250 grams per square meter, respectively. The overall construction of reinforcements is given in ***Table 1***.

Thermosetting of unsaturated polyester resin was used due to easy handling, curing at room temperature and its low cost [28]. Cobalt naphthalene was used as a hardener and poly-ethyl-ether ketone as an accelerator for thermoset unsaturated polyester. The hardener and accelerator were used in an amount of 0.2% and 1.0% of the resin quantity, respectively.

The methods involve the manufacturing and treatment of reinforcements as well as the fabrication and characterization of the composites. Reinforcements were prepared on a weaving machine, and subsequently enzymatic desizing and scouring was done as a pretreatment of cotton and jute, respectively. The desizing was performed using enzyme Beisol (2 g/l) for 30 min and the temperature was maintained at 70-80 °C. Scouring of the jute fabric was done for 40 min at a temperature of 80-90 °C to remove impurities. The recipe used for scouring was:

- NaOH: 10 g/l
- Wetting agent: 2 g/l
- Sequesting agent: 2 g/l
- Detergent: 2 g/l

The composite samples fabricated for this study were laminated, each having six plies of the reinforcement. All the plies were placed in a [0°] (or warp direction) stacking sequence (***Figure 1***) and a total of seven samples were fabricated with different percentages of cotton, jute, and glass. Out of seven, three samples were fabricated with a single type of reinforcement. Four hybrid composite samples were produced in such a way that there were different numbers of plies for cotton, jute and glass, enabling to achieve different percentages of materials in different composite samples. Details of the hybrid composite samples are as follows, while their percentage is given in ***Table 2***.

- Sample 1 had four plies of cotton and one ply of jute and glass each
- Sample 2 had three cotton plies, two jute plies and one glass ply
- Sample 3 had two plies for cotton, jute and glass each
- Sample 4 had one cotton ply, two jute plies and three glass plies
- Sample 5, 6 and 7 were produced using all plies of cotton, jute and glass, respectively.

The vacuum bag molding technique was used to manufacture composite samples. This method helps to produce a more uniform composite part by removing the air bubbles, and hence better consolidation of layers is achieved [29]. A negative pressure of -1 bar was applied by means of a vacuum. The fiber volume fraction was maintained at 30%. The initial cur-

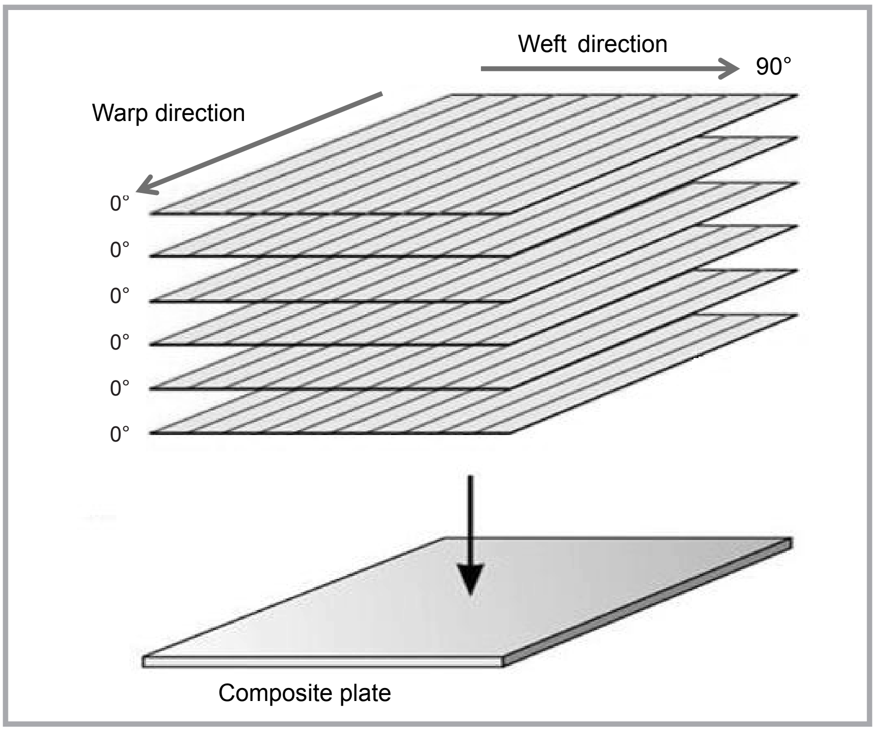

Figure 1. *Schematic illustration of stacking of fabric plies into a composite laminate.*

Table 1. *Description of reinforcements.*

No.	Reinforcement	Areal density, g/m^2	Warp count, tex	Weft count, tex	Ends/cm	Picks/cm
1	Cotton	200	29.5	34.7	43	20
2	Jute	270	295	295	5	5
3	Glass	250	118	118	5	5

Table 2. *Percentage of different reinforcements in composite samples.*

Sample No.	Cotton %	Jute %	Glass %
1	66.6	16.7	16.7
2	33.3	50.0	16.7
3	33.3	33.3	33.3
4	33.3	16.7	50.0
5	100	–	–
6	–	100	–
7	–	–	100

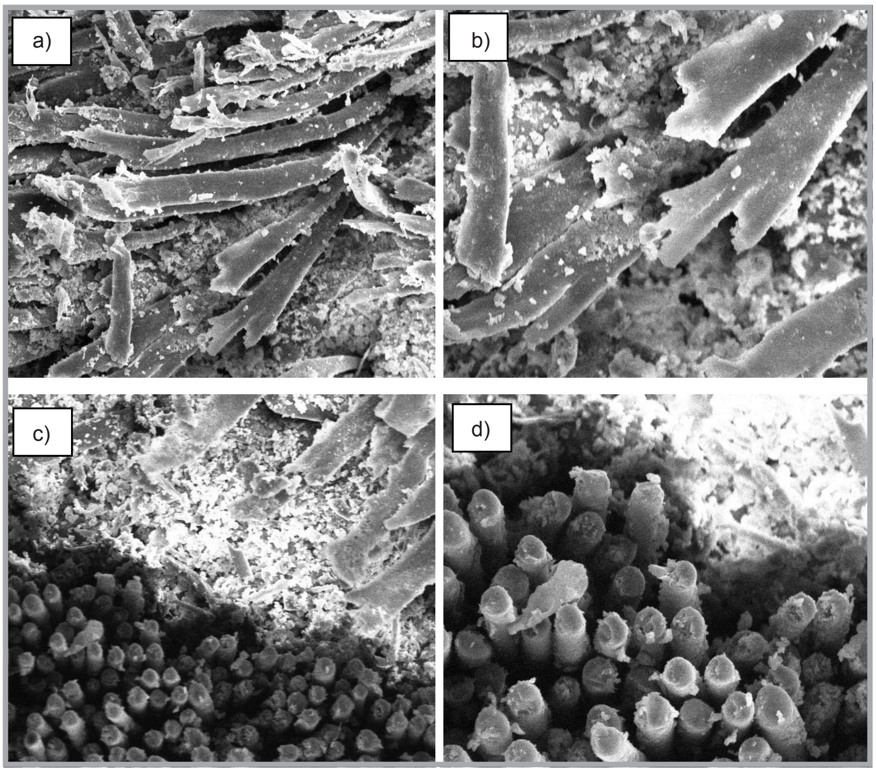

__Figure 2.__ SEM image of hybrid composite sample (a) & (b) sample 2, (c) & (d) sample 3.

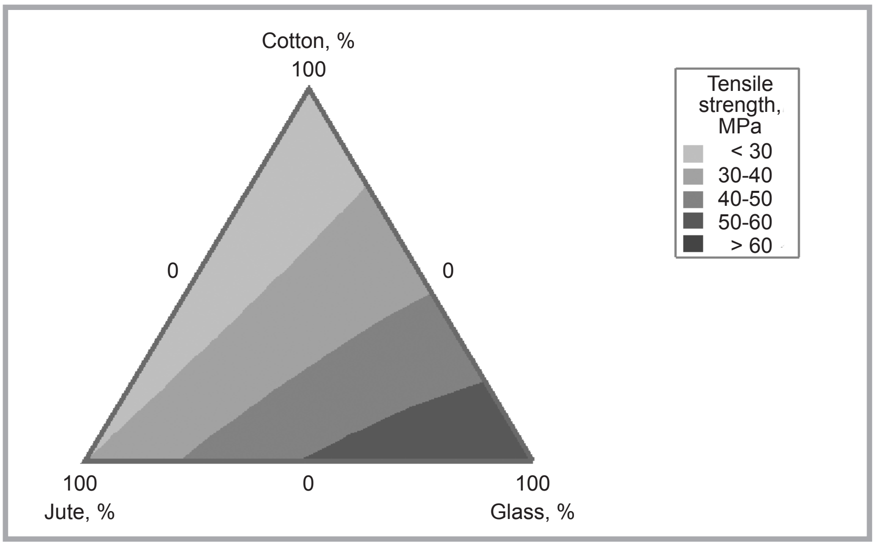

__Figure 3.__ Contour plot of tensile strength.

ing was performed at room temperature for four hours and then post curing was done at 120 °C for two hours in an oven. Scanning electron microscopy of the composite samples developed was performed using a TESCAN VEGA3 SEM system (Czech Republic). The tensile properties (tensile strength and tensile modulus) of these composite materials were tested using ASTM D3039, while three point flexural properties (flexural strength and flexural modulus) were tested according to the test method ASTM D7264. Tensile and flexural properties of the samples were tested on an Instron 4411 Universal Tensile Testing machine (USA) at room temperature. The dynamic mechanical properties of the composites developed were investigated according to the test method ASTM D5279 on an DMA Q800 instrument by TA (USA).

Results and discussion

To investigate the composite material samples developed for interface and mechanical performance under certain loads, several tests were employed, as discussed in the previous section. The reinforcements in these hybrid composites were jute, glass and cotton. Cotton and jute are nature based, while glass fiber is synthetic. This heterogeneous nature of reinforcements might result in poor interfacial adhesion. The interfacial adhesion between different reinforcing materials in the hybrid composite sample was established by scanning electron microscopy (SEM), given in ***Figure 2***. It can be observed from the images that despite the heterogeneous nature of the reinforcement, there is good interface developed among the different reinforcements and also with the matrix. Hence the matrix can transfer the load easily to the reinforcement without any possibility of delamination, and the fibers fully contribute to the mechanical properties of the composites.

Tensile strength

Tensile properties of the composite samples were analysed, and a contour plot for the tensile strength against different percentages of cotton, jute and glass reinforcement in the composite samples is given in ***Figure 3***. It can be observed that the plot is divided into four coloured segments, each representing a specific range of tensile strength from <30 MPa to >60 MPa. The highest range of tensile strength (>60 MPa) is represented by the darkest coloured segment. The tensile strength of the composite is affected by the percentage of reinforcing materials (cotton, jute and glass), shown by each corner of the graph.

It is obvious from ***Figure 3*** that the composite with 100% cotton as reinforcing material has a tensile strength in the region of 20 MPa because the mechanical properties of cotton are lower than for jute and glass [26]. A large change in the tensile strength of the composite is not observed when using both natural fibers i.e. jute and cotton as reinforcing materials, because the mechanical properties of natural fibers are lower than for glass fibers [30]. The tensile strength of hybrid composites with different percentages of cotton, jute and glass fibers is between 40-60 MPa. The composite with 100% glass fibers as reinforcing material has a tensile strength of more than 60 MPa because the mechanical properties of glass are higher than for cotton and jute fibers [11].

Figure 4 shows a main effect plot for percentages of reinforcing materials (cotton, jute and glass) against the tensile strength of the composite samples. In the main effect plot, the factor (reinforcing material) whose slope is steeper than others imparted a large effect on the response variable (tensile strength).

It is obvious from the graph that the slopes of cotton are steeper than that of jute, the tensile strength of the composite samples is decreased by increasing the percentage of cotton. While the strength is increased by increasing the percentage of glass, because the tensile strength of glass fibers is greater than for cotton [31].

The slope of jute showed that tensile strength does not change abruptly by increasing the percentage of jute because the tensile strength of jute is midway between that of cotton and glass [32].

$$\text{Tensile strength (MPa)} = 23.10\ X_1 + 30.19\ X_2 + 60.27\ X_3 – 13.87\ X_1\ X_2 – + 13.85\ X_1\ X_3 + 22.09\ X_2\ X_3$$

$$R^2 = 99.84$$

This regression equation showed a mathematical relationship between the response (tensile strength) and factors (percentages of reinforcing materials), where X_1, X_2, and X_3 are the percentages of cotton, jute and glass, respectively. It is not built from one sample, rather the test results of all seven samples were used to formulate the equations, with all samples having varying percentages of the materials (cotton, jute and glass). The coefficient of determination (R^2) showed that X_1, X_2, and X_3 satisfied the given equation by 99.84%. The response (tensile strength) is largely affected by the factor (reinforcing material) whose coefficient is more than for the others. Thus it is clear from the equation that the tensile strength is largely affected by t factors X_3 and X_2 x X_3.

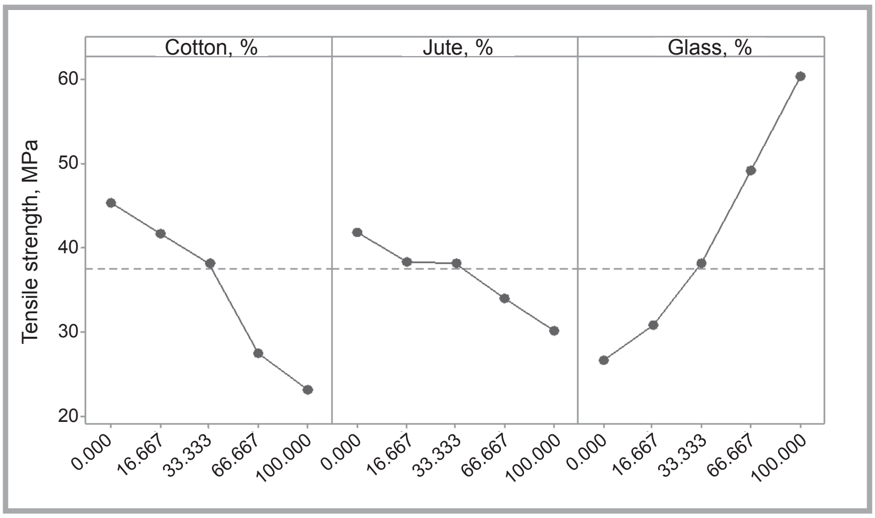

Figure 4. Main effect plot for tensile strength.

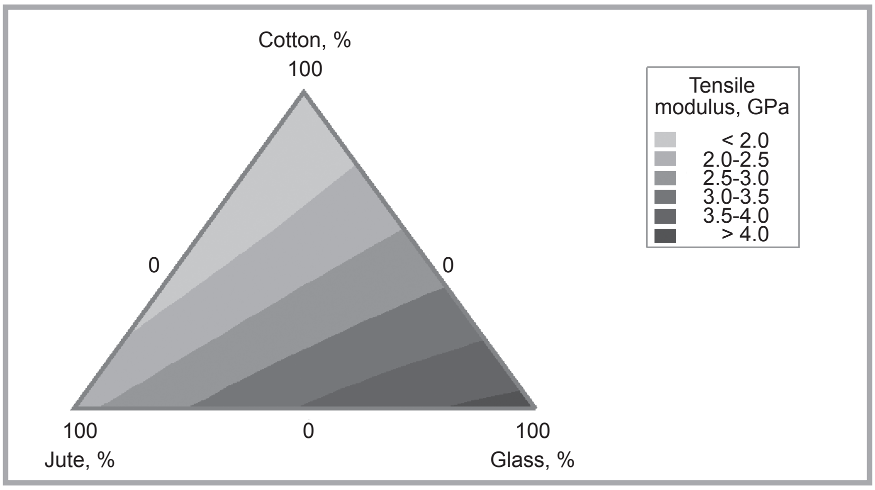

Figure 5. Contour plot of tensile modulus.

Tensile modulus

Figure 5 shows a contour plot for the tensile modulus against the percentages of cotton, jute and glass in the composite samples. This graph is divided into six coloured segments, each represented by a specific range of tensile strength, from <2 GPa to >4 GPa. The highest range of tensile modulus (>4 GPa) is represented by the darkest coloured segment. The tensile modulus of the composite is affected by the percentage of reinforcing materials (cotton, jute and glass), shown by each corner of the graph.

It is clear from the graph that the composite with 100% cotton as reinforcing material has a tensile modulus in the region of 2 GPa because the mechanical properties of cotton are lower than for jute and glass [26]. A large change in the tensile modulus is not observed when using both natural fibers i.e. jute and cotton as reinforcing materials because the mechanical properties of natural fibers are lower than for glass fibers [30]. The tensile modulus of hybrid composites with different percentages of cotton, jute and glass fibers is between 2.6 GPa and 4 GPa. The composite with 100 % glass fibers as reinforcing material has a tensile modulus more than 4 GPa because the mechanical properties of glass are higher than for cotton and jute fibers [11].

Figure 6 shows a main effect plot for the percentages of reinforcing materials (cotton, jute and glass) against the tensile modulus of the composite samples. In the main effect plot, the factor (reinforcing material) whose slope is steeper than others imparted a large effect on the response variable (tensile modulus).

The tensile modulus of the composite samples is decreased by increasing the percentage of cotton. While the modulus is increased by increasing the percentage of glass, because the tensile strength of glass fibers is greater than for cotton [31].

$$\text{Tensile modulus (GPa)} = 1.52\ X_1 + 1.93\ X_2 + 4.46\ X_3 + 0.36\ X_1\ X_2 + 0.54\ X_1\ X_3 + 0.18\ X_2\ X_3$$

$$R^2 = 99.20\%$$

This regression equation showed a mathematical relationship between the response (tensile modulus) and factors (percentages of reinforcing materials), where X_1, X_2, and X_3 are percentages of cotton, jute and glass, respectively.

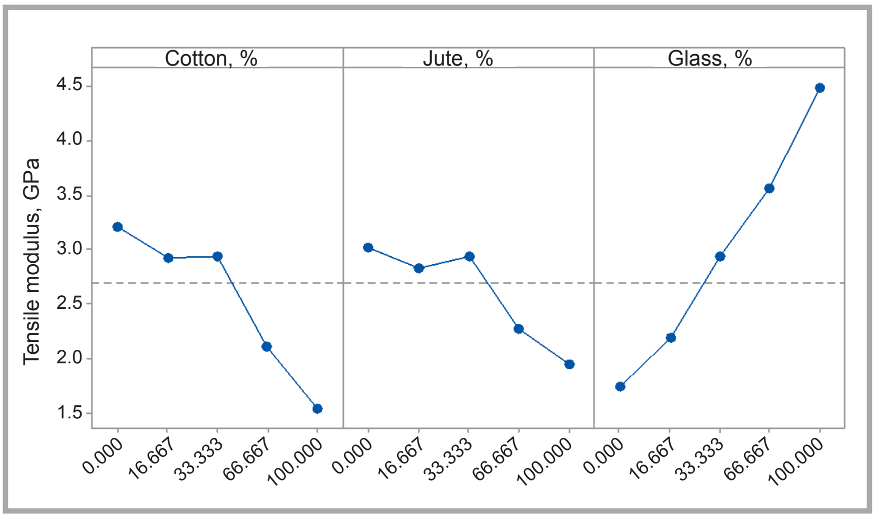

Figure 6. Main effect plot for tensile modulus.

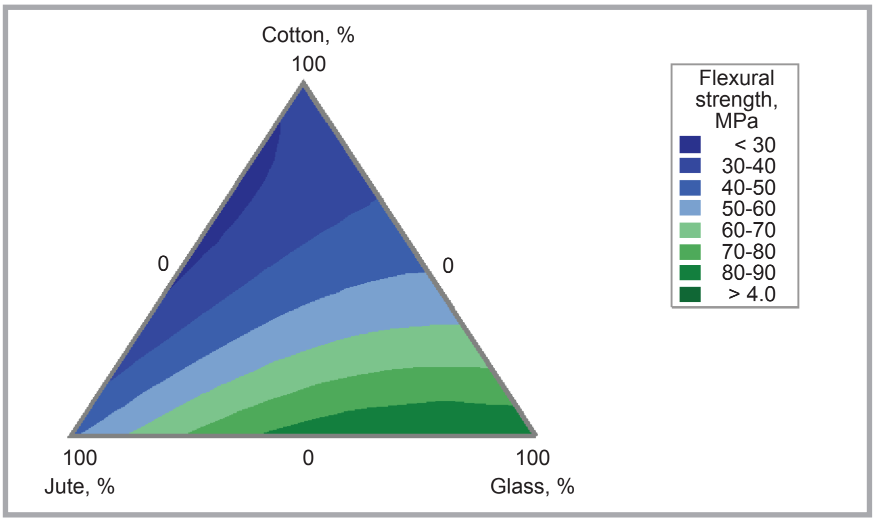

Figure 7. Contour plot of flexural strength.

The coefficient of determination (R^2) showed that X_1, X_2, and X_3 satisfied the given equation by 99.20%. The response (tensile modulus) is largely affected by the factor (reinforcing material) whose coefficient is more than the other. Thus it is clear from the equation that the tensile modulus is largely affected by factors X_3 and X_1 x X_3.

Flexural strength

Figure 7 shows a contour plot for the flexural strength against different percentages of cotton, jute and glass in the composite samples. This graph is divided into seven coloured segments, each represented by a specific range of flexural strength from <20 MPa to >90 MPa. The highest range of flexural strength (>90 MPa) is represented by the darkest coloured segment. The flexural strength of the composite is affected by the percentage of reinforcing materials (cotton, jute and glass), shown by each corner of the graph.

It is clear from the graph that for the composite with 100 % cotton as reinforcing material, the flexural strength is in the region of 20 MPa because the mechanical properties of cotton are lower than for jute and glass [26]. A large change in flexural strength is not observed when using both natural fibers i.e. jute and cotton as reinforcing materials, because the mechanical properties of natural fibers are lower than for glass fibers [30]. The flexural strength of hybrid composites with different percentages of cotton, jute and glass fibers is between 40-90 MPa. The composite with 100% glass fibers as reinforcing material has a flexural strength more than 90 MPa because the mechanical properties of glass are higher than for cotton and jute fibers [11].

Figure 8 shows a main effect plot for the percentages of reinforcing materials (cotton, jute and glass) against the flexural strength of the composite samples. In the main effect plot, the factor (reinforcing material) whose slope is steeper than others imparted a large effect on the response variable (flexural strength).

The flexural strength of the composite samples is decreased by increasing the percentage of cotton. While the strength is increased by increasing the percentage of glass, because the flexural strength of glass fibers is greater than for cotton [31].

$$\text{Flexural strength (MPa)} = 33.01\ X_1 + 48.93\ X_2 + 88.72\ X_3 - 51.37\ X_1 X_2 - + 51.07\ X_1 X_3 + 64.25\ X_2 X_3$$

$$R^2 = 99.77\%$$

This regression equation showed a mathematical relationship between the response (flexural strength) and factors (percentages of reinforcing materials), where X_1, X_2, and X_3 are percentages of cotton, jute and glass respectively. The coefficient of determination (R^2) showed that X_1, X_2, and X_3 satisfied the given equation by 99.77%. The response (flexural strength) is largely effected by the factor (reinforcing material) whose coefficient is more than the other. Thus it is clear from the equation that the flexural strength is largely affected by factors X_3 and X_2 x X_3.

Flexural modulus

Figure 9 shows a contour plot for the flexural modulus against different percentages of cotton, jute and glass in the composite samples. This graph is divided into six coloured segments, each represented by a specific range of flexural modulus from <1 GPa to >2 GPa. The highest range of flexural modulus (>2 GPa) is represented by the darkest coloured segment. The flexural modulus of the composite is affected by the percentage of reinforcing materials (cotton, jute and glass), shown by each corner of the graph.

It is clear from graph that the composite with 100% cotton as reinforcing material has a flexural modulus in the region of 1 GPa because the mechanical properties of cotton are lower than for jute and glass [26]. A large change in the flexural modulus is not observed when using both natural fibers i.e. jute and cotton as reinforcing materials because the mechanical properties of natural fibers are lower than for glass fibers [30]. The flexural modulus of hybrid composites with different percentages of cotton, jute and glass fibers is between 1.5 and 2.0 GPa. The composite with 100% glass fibers as reinforcing material has a flexural modulus more than 2 GPa because the mechanical properties of glass are higher than for cotton and jute fibers [11].

Figure 10 shows a main effect plot for the percentages of reinforcing materials (cotton, jute and glass) against the flexural modulus of the composite samples. In the main effect plot, the factor (reinforcing material) whose slope is steeper than the others imparted a large effect on the response variable (flexural modulus).

The flexural modulus of the composite samples is decreased by increasing the percentage of cotton. While the modulus is increased by increasing the percentage of glass, because the flexural modulus of glass fibers is greater than for cotton [31].

$$\text{Flexural modulus (GPa)} = 0.76\, X_1 + 1.18\, X_2 + 2.10\, X_3 - 0.45\, X_1 X_2 + 0.35\, X_1 X_3 + 0.53\, X_2 X_3$$

$$R^2 = 99.98\%$$

This regression equation showed a mathematical relationship between the response (flexural modulus) and factors (percentages of reinforcing materials), where X_1, X_2, and X_3 are percentages of cotton, jute and glass, respectively. The coefficient of determination (R^2) showed that X_1, X_2, and X_3 satisfied the given equation by 99.98%. The response (flexural modulus) is largely affected by the factor (reinforcing material) whose coefficient is more than the others. Thus it is clear from the equation that the flexural modulus is highly affected by factors X_3 and $X_2 X_3$.

Dynamic mechanical analysis

Dynamic mechanical analysis (DMA) tests of the composites developed were performed using a TA instrument – DMA Q800. In DMA, a fluctuating load is applied to the composite sample, and the strain is measured as a function of the temperature. It splits the dynamic modulus (E) into an elastic (storage modulus, E') and viscous (loss modulus, E") component. The ratio of *E"* to *E'* is known as the damping coefficient (tan δ) and is a measure of energy dissipation. These parameters provide quantitative and qualitative information about the material behaviour.

The effect of temperature on the elastic and viscous modulus of the composites with varying percentages of cotton reinforcement is shown in ***Figure 11***. ***Figures 11.a*** and ***11.b*** represent DMA results of the composite with almost equal fractions of cotton, jute and glass reinforcement and that produced from only cotton reinforcement. A variation occurs in the modulus, which may be attributed to the effect of the reinforcing material. A large decrease can be observed in the storage and loss modulus with increasing temperature in both composite samples. However, the difference between the moduli of the glassy state and rubbery state is smaller in composites reinforced with equal fractions of cotton, jute and glass as compared to the all-cotton composite. This may be attributed to the dynamic effect of the fibers embedded and to their mechanical properties, which reduce the mobility of the matrix. A higher percentage of cotton gives a lower storage modulus at low temperatures, which may be due to the moisture absorption of cotton. At temperatures higher than 100 °C, absorbed water evaporates and both composites show a similar value of storage modulus. The variation in the loss modulus with temperature is a bit complex, i.e. higher for the all-cotton composite below 60 °C and decreasing at higher temperatures.

Conslusions

The study concluded that the tensile and flexural properties of the composites developed from waste material were found lower as compared to the glass fiber composites, while hybrid composites had comparable properties. Regression equations were also developed to predict the mechanical properties of the hybrid composites. The dynamic mechanical analysis (DMA) results revealed that after some pre-treatment (mercerization and desizing) textile waste materials can be used with virgin material in the reinforcement part of the composite to decrease the cost, but with optimum mechanical properties. This usage of textile waste will be helpful for its value addition and solving waste disposal problems.

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