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Research Article

Effect of Fiber Length on Properties of Jute Fiber Reinforced Polymer Matrix Composite

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Abstract

Natural fibers have recently become attractive as an alternative reinforcement for fiber reinforced polymer (FRP) composites due to their low cost, fairly good mechanical properties, high specific strength, non-abrasive, eco-friendly and bio-degradability characteristics. In this work, an investigation is carried out on jute fiber, a natural fiber that has gained interest in the composite field due to its superior specific properties compared to manmade synthetic fibers. The present work describes the development of natural fiber based composites consisting of raw jute fiber as reinforcement and polystyrene as matrix material. 5% (w/w) jute fiber fillers of lengths 10 mm, 20 mm and 30 mm respectively were prepared. The composites were fabricated using hand lay-up molding technique. Mechanical properties of the developed composites were investigated using Tensile, Flexural and Hardness Tests. Thermo-Gravimetric Analysis (TGA) was further done to fully understand the stability of the composites. The Critical fiber length required for Raw Jute Fiber Reinforced Polymer matrix composite was also determined and the properties were compared with respect to critical fiber length. The results reveal that, the mechanical properties of polystyrene based composites are substantially improved on account of the addition of the jute fiber reinforcement. Significant amount of improvement is achieved for 20 mm and 30 mm fiber length composites.

Keywords: Jute fiber; Polystyrene; Composites; Critical fiber length; Mechanical Properties.

Introduction

In modern day engineering and development works, materials with conflicting and unusual properties are often required that cannot be met by tradition materials available such as metals, polymers, etc. To meet these property requirements, composites are being developed. Among the various types of composites, fiber reinforced polymer composite possess great importance which is a composite material consisting of a polymer matrix imbedded with high-strength fibers [1]. Recently, natural fibers as reinforcement in polymer composites have attracted the attention of many researchers and scientists due to their low cost, low density, comparable specific tensile properties, non-abrasive to the equipment, non-irritation to the skin, reduced energy consumption, less health risk, renewability, recyclability and bio-degradability [2].

One of the most trending natural fibers to be used in recent composite developments is jute fiber. Due to its ease of availability and increasing demand as environmental friendly material, jute fiber has become important in composite engineering. It has relatively low density and higher strength and modulus than plastic and is a good substitute for conventional fibers in many situations [3].

The mechanical properties of composites are markedly improved by adding fibers to a polymer matrix since fibers have much higher strength and stiffness values than those of the matrices. For effective strengthening and stiffening of composite materials by fiber reinforcement, a critical fiber length is necessary. Critical fiber length L_c is the minimum length at which the center of the fiber reaches the ultimate (tensile) strength σ_f, when the matrix achieves the maximum shear strength τ_c. When the fiber length is below critical fiber length, the failure will no longer involve fracture of the fibers and will be governed by fiber pull-out [4]. It is often observed that the increase in fiber loading leads to an increase in tensile

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properties [5]. In a study in 1996 it has been shown that strength of short fiber reinforced composite increases rapidly with the increase of the mean fiber length (in the vicinity of the critical fiber length, L_c) and approaches a plateau level as the mean fiber length increases ($>5L_c$) [6].

The present study deals with the fabrication and property analysis of composites consisting of polystyrene as matrix material and raw jute fiber as fillers. Generally, polystyrene is a synthetic aromatic polymer which is hydrophobic in nature. It consists of long hydrocarbon chains with large total attractive force between the molecules resulting in chemical inertness. On the other hand, natural fibers such as jute are hydrophilic in nature as they are derived from ligno-cellulose. So this results in inferior interfacial adhesion between polar-hydrophilic fiber and nonpolar-hydrophobic matrix. The mechanical properties are controlled mainly by the efficiency of the bonding at the fiber-matrix interfacial boundary which facilitates the transfer of stress from fiber to fiber, across the matrix [7]. Numerous research studies conducted over the last decade have reported successful use of different fibers such as hemp, sisal, coconut, jute, sugarcane bagasse, etc. as reinforcement to enhance the mechanical properties of the polystyrene based composites [8-12]. However, not much work has been reported particularly on the effect of jute fiber lengths on polystyrene matrix composite. Therefore, the main challenge in this study is to observe the mechanical and thermal behavior of the composites after embedding raw untreated jute fibers of variable fiber lengths.

Material and methods

Materials

The materials employed in this investigation were i. Polystyrene (PS) resin (Collected locally from Dhaka, Bangladesh), ii. Jute fiber (Produced in Rangpur region of Bangladesh) and iii. hardener (Collected locally from Dhaka, Bangladesh).

Critical fiber length measurement

First, the fiber diameters of 40 fibers were measured using microscopic measurement technique. The average diameter (d) of the fiber was found to be 0.103 mm and cross sectional area (A) was calculated to be 8.33×10^{-3} mm^2. 30 fibers were taken together for tensile test totaling a cross sectional area of 0.249 mm^2. Universal testing machine (UTM) of model INSTRON 3369 was used for fiber tensile test. It was found that the Average Load was 0.029 kN, Tensile Strength of jute fiber was 116.5 Mpa and the Maximum shear strength for polystyrene, τ_c was 25 Mpa [8]. Critical Fiber Length, $L_c = (\sigma_f \times d)/2\tau_c$ was then calculated. It was found to be 0.24mm. Therefore, for continuous fiber, the fiber length was determined to be greater than or equal to 3.6 mm ($L \geq 15L_c$).

Composite fabrication

To fabricate composites, the raw jute fibers were washed with clean water to remove any kind of dirt, silt, etc. Then they were naturally dried followed by oven drying at 80°C for 6 hours. Finally, the fibers were cut into lengths 10 mm, 20 mm and 30 mm respectively. For the hand lay-up method of composite fabrication, a mold of 160 mm×160 mm×10 mm was prepared. Appropriate amount of Polystyrene resin needed for each casting was measured and then it was vacuum treated for 15 minutes to remove dissolved gasses. After that, 5% wt. of raw jute fibers (for every 100 gm polystyrene, 5 gm jute was taken) of desired length was measured. The jute fibers were preheated to remove any undesirable moisture. Fibers were then mixed with the matrix. The final mix was vacuum-treated for 15 minutes followed by the addition of 1% hardener and mixing. The mix was quickly poured in the mold and properly spread. A roller was used for further spreading and also for smoothening of the top surface. It was kept like this for 24 hours to harden and transform into desired composite. Pure polystyrene sample was also fabricated in this method.

Mechanical behavior analysis

Tensile and flexural test specimens were prepared according to standard specification. Universal Testing Machine of model INSTRON 3369 was used for the tests and they were performed at a cross-head speed of 2 mm/min. Tests were conducted according to ASTM D 638-01. For each type of composite, several replicate samples were tested and the average values were reported. The results were analyzed to see the effective changes. The hardness of the fabricated composites and the pure PS was measured using HPE Shore A hardness tester.

Thermo-gravimetric Analysis

Pure Polystyrene and Composites Samples of 2mm×2mm×2mm size and weight between 15 to 20mg were prepared for Thermo-Gravimetric Analysis(TGA). The tests were conducted using SETARAM TGT DTA 92 thermo-gravimetric apparatus. The mass variation of the sample was measured as a function of temperature under an inert gas nitrogen atmosphere up to 650° C. The test data were used for further analysis.

Results and discussion

Mechanical behavior

Jute fiber reinforcement effect on mechanical properties of polystyrene composite are demonstrated. As depicted in figure 1, the tensile strength linearly increases with the increase in fiber length. Although the incorporation of 10 mm fibers did not help much, larger fiber lengths did contribute in increasing strength. Significant improvement was achieved for 30 mm fiber length.

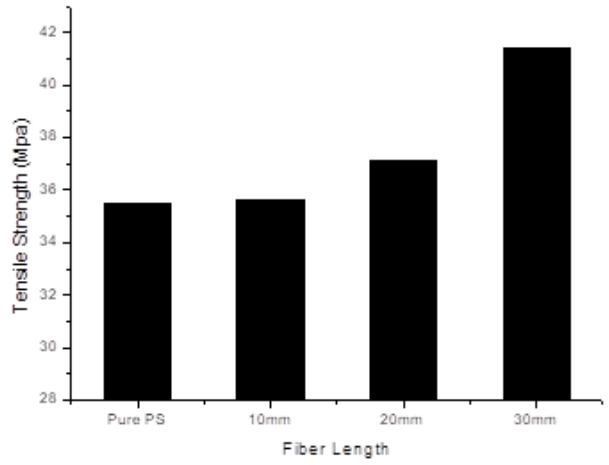

Figure 1. Tensile strength comparison between pure and composite samples with the increase in fiber length

The mechanical properties of composites are influenced mainly by the adhesion between matrix and fibers. Polystyrene molecules are long hydrocarbon chains that consist of thousands of atoms, the total attractive force between the molecules is large, resulting in chemical inertness. On the other hand, natural fiber jute is hydrophilic in nature as it is derived from ligno-cellulose, which contains polarized hydroxyl groups. This results in inferior interfacial adhesion between polar-hydrophilic fiber and nonpolar-hydrophobic matrix, resulting in poor wetting of the fiber with the matrix [13]. This might be the reason for the insignificant change of tensile strength for 10 mm fiber length composite. The mechanical properties are controlled mainly by the efficiency of the bonding at the fiber-matrix interfacial boundary which facilitates the transfer of stress from fiber to fiber, across the matrix [7].

A linear improvement in tensile strength was observed with the increase in fiber length. It has been mentioned that jute fibers have relatively low density and higher specific strength and modulus than plastic [3]. The diameter remained constant for fibers. Therefore, with the increase in fiber length, higher fiber aspect ratios (length to diameter ratio) where achieved which might lead to higher composite strengths [11]. Moreover, under tensile loading, the cracks start at the fiber ends and propagate along the fiber–matrix interface or cross through the matrix, and finally the failure takes place. Fiber ends have been shown to substantially concentrate the stress in the adjacent matrix, producing stress magnifications. The effects of these stress concentrations can be relieved only by matrix flow, interface de-bonding or matrix fracture or cracking. For short fibers, there is a "bridging" effect of the micro-cracks due to the fibers being close to each other and also higher number of fibers if the volume kept constant, leading to the final failure. So, the failure mechanism of composites is closely related to the number of fiber ends. In this research, the volume fraction of fibers remained constant in all the composites. Therefore, large fiber lengths resulted in less fiber ends compared to short fibers (Number of fibers increases for short fiber), resulting in less stress concentration points and also less bridging effect due to longer distance between the fibers. This might explain the improvements observed with the increase in fiber lengths. It might also be noted that, 20 mm and 30 mm fiber which has lengths 83 and 125 times greater than the critical length, which indicates that for effective strengthening, much higher lengths were needed compared to critical length for raw jute fiber.

Figure 2 states the % elongation comparison. It can be seen that there is a decreasing trend in % elongation. A sharp drop can be observed when stiff fibers are introduced in the matrix and the gradual increase in fiber length resulted in further decrease in elongation. This decline in elongation on filler addition is because the fibers in the matrix restrict the

plastic flow of the polymer [14]. As stated previously, the inferior interfacial adhesion between polar-hydrophilic fiber and nonpolar-hydrophobic matrix results in poor wetting of the fiber with the matrix which leads to significant drop in properties. Generally, the filler fibers tie polymer chain bundles together by filling interstitial voids, thereby restricting molecular slippage on application of tensile force and distributing any induced stress more equitably. However due to inferior wetting and bonding between the matrix and fiber, the stress transfer is not much effective. This attributes to the reduction in plastic flow with increased fiber length resulting in decrease in elongation.

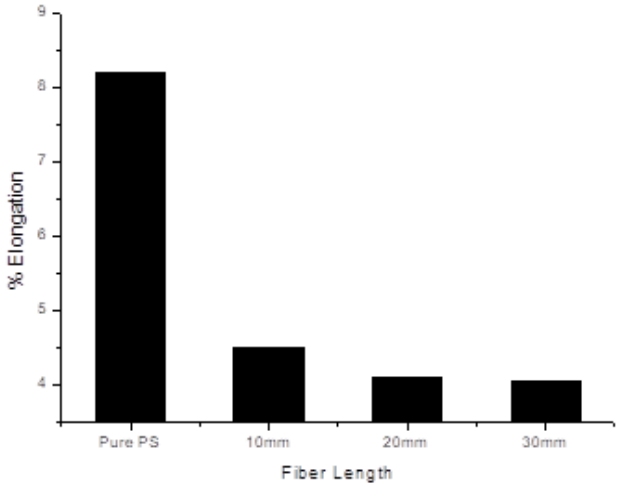

Figure 2. % elongation comparison between pure and composite samples with the increase in fiber length

Tensile modulus comparison is further shown in Figure 3. This also shows an increasing trend with the fiber lengths. We know that tensile modulus is an indication of the relative stiffness of the material. Therefore, we can conclude that there is a gradual increase of stiffness with increase in fiber length. This rise in stiffness might be due to the fact that, the increase in the length of Jute fiber in the polystyrene matrix reduces the matrix mobility [7,15]. Also as discussed previously, the addition of the rigid fibers into the soft PS matrix results in poor interfacial bonding which creates partially separated micro-spaces between the filler and matrix polymer thereby obstructing stress propagation during tensile stress loading, resulting in increased stiffness [16].

Figure 4 illustrates the flexural strength of the composites with different fiber lengths. The flexural strength goes up linearly with an increase in fiber length. The incorporation of 10 mm and 20 mm fibers result in slight improvements. However, noticeable improvement is observed for 30 mm fiber length composite. A flexural test is highly influenced by the properties of the specimen closest to the top and bottom surfaces, whereas a simple tension test reflects the average property through the thickness [17]. Jute fiber, in our case increased the flexural strength as the length increased which might be due to the increased aspect ratio (length to diameter ratio) with the increase in the fiber length [18]. Noticeable improvement can be seen for 30 mm fiber length, which is almost 125 times greater than the critical length.

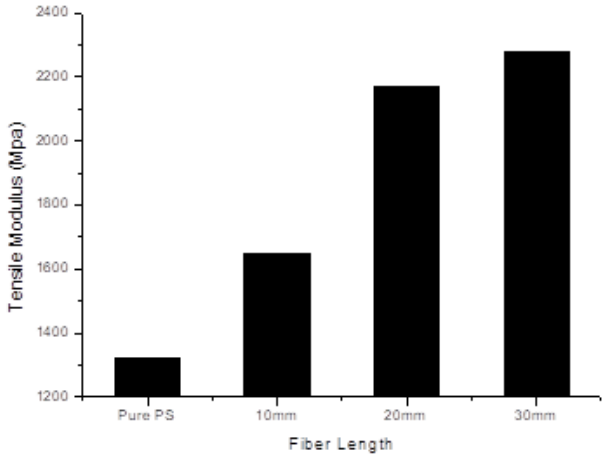

Figure 3. Tensile modulus comparison between pure and composite samples with the increase in fiber length

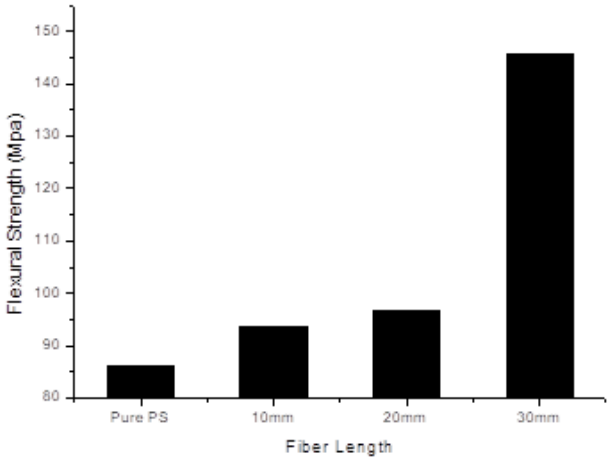

Figure 4. Flexural strength comparison between pure and composite samples with the increase in fiber length

Hardness comparison in figure 5 shows the same trend like the rest of the mechanical tests. It can be seen that, there is an increase in

hardness for composites compared to pure polystyrene. This might be due to increased stiffness of composites discussed previously. The addition of the rigid fibers into the soft PS matrix results in increased stiffness as the poor interfacial bonding creates partially separated micro-spaces between the filler fiber and polymer matrix thereby obstructing stress propagation during tensile stress loading [16].

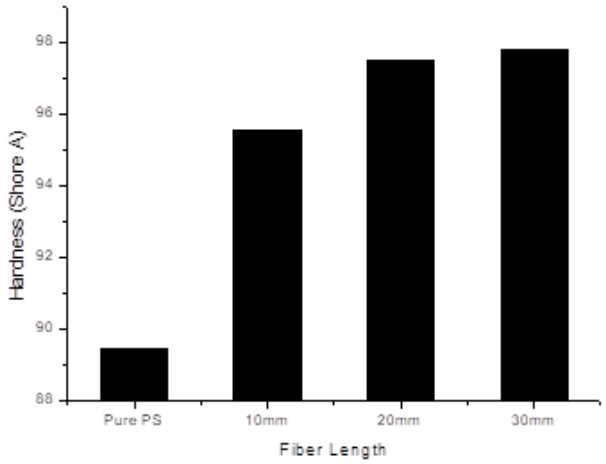

Figure 5. Hardness comparison between pure and composite samples with the increase in fiber length

Thermal analysis

Thermal stability of Jute Fiber Reinforced Polystyrene composites is necessary in determining their application and end use. The effect of different lengths of Jute on the thermal degradation of the composites was investigated and the TGA curves are combined in figure 6. A sudden drop in the mass of the sample indicated the thermal degradation of the material. The materials started to thermally degrade at 300 °C, and decomposed at 520 °C, where substantial loss in their weights was observed. The curve also shows that thermal degradation began to occur only after the materials have absorbed certain amounts of heat energy which initiated the degradation processes and the breaking down of the fibers and matrix structure by causing molecular chain ruptures. If we analysis the results further from Table 1, we can conclude that composites show higher thermal stability than pure polystyrene and also thermal stability of the composites increased with the increase in fiber length.

As can be seen, the incorporation of jute fibers to the Polystyrene matrix, in general, increased the degradation temperature of the composites. As the fiber lengths increased, there was a shift upward of the degradation temperature. The introduction of fillers into poly-alkanes usually results in an increase of the thermal stability of the polymer [19]. The heat absorption capacity of filler fibers contributes to the overall stability of the composites. In general, polystyrene has a comparatively low thermal stability due to its volatile nature. When the addition of jute fiber is made they cover the polystyrene grains and therefore tend to decrease its volatility, as a result improving its thermal stability. This is due to the fact that heat absorption capacity of jute fiber is higher than polystyrene. The heat absorption capacity of filler fibers contributes to the overall stability of the composites.

Table 1. Percentage weight loss composites at different temperatures

Weight Loss, %	Temperature, °C			
	Pure Polystyrene	10 mm	20 mm	30 mm
10	307.74	310.38	314.02	320.94
20	339.63	341.4	341.29	348.13
30	355.26	355.51	354.88	361.73
40	365.35	365.26	365.06	371.89
50	374.93	372.88	373.37	380.13
60	383.98	379.1	380.7	387.51
70	392.9	386.29	387.2	393.75
80	402.22	396.13	396.14	402.99
90	413.02	475.48	480.72	487.56
93	418.07	508.71	511.46	518.24

A step in the TGA curves for composites were observed compared to pure polystyrene at about temperature ranging from 400 to 550 °C. The thermal disintegration of plant fibers such as jute comprises of four phases. The initial phase involves the breakdown of hemicelluloses, followed by that of cellulose, and of lignin, and finally of their ash [20]. Usually the decomposition of hemi-cellulose continues up to 315°C followed by the decomposition of cellulose which is relatively thermally stable due to its highly crystalline nature. It is than followed by the decomposition of lignin, a compound known to give rigidity to the plant material, which is the hardest to decompose and might need as high as 900 °C to complete [21]. This phenomenon might perfectly explain the step in the curves and the prolonged decomposition for jute fiber composites. As the length of fibers increased, the fibers in the composites absorbed more heat, therefore higher temperature was required to achieve the threshold energy for

commencement of the degradation process. Thus there was a shift upward of the degradation temperature.

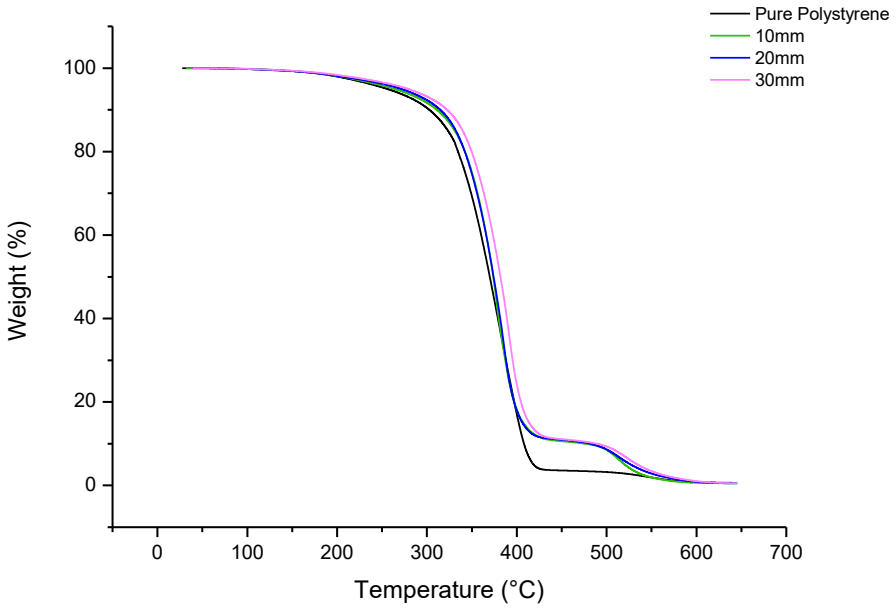

Figure 6. TGA Curves of pure and composite samples

Conclusions

This study suggests that the incorporation of jute into the polystyrene results in improved mechanical properties. The composite shows an increasing trend in mechanical behavior and thermal stability with the increase in fiber lengths. Noticeable improvements in tensile strength and modulus can be observed for larger fiber lengths. The flexural strength linearly increased with the fiber length. The hardness values for the composites were better compared to polystyrene since the introduction of rigid fibers into the matrix results in increased stiffness. Thermo-Gravimetric Analysis (TGA) results have shown that thermal stability of the composites increased with the increase of fiber length. The thermal degradation of composites with different fiber length improved compare to unfilled polystyrene. Composite containing jute fibers of length 30 mm which is almost 125 greater than the critical fiber length, demonstrated the most effective strengthening and thermal stability. Therefore, it can be concluded that larger fiber lengths result in improved properties for polystyrene based composites containing jute fibers as filler.

Conflicts of interest

Authors declare no conflict of interest.

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