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Tensile Properties of Jute-Polypropylene Composites

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This paper describes the tensile behaviour of jute-polypropylene fibre composites with different fibre volume fractions. Here, the composite laminates consisting of weaving jute fibres, with the fibre volume percent in the range of 20 to 80 % and polypropylene plies were prepared using hand lamination. The composite laminates were subjected to tensile testing as per ASTM D3039. The experimental results suggested that fibre-to-resin contents have a strong influence on the tensile properties of the composites. There is an increase in the tensile strength and Young's Modulus of the composites with increasing fibre volume fraction. However, upon reaching 60 % of the fibre contents, the tensile properties of the laminate showed a sudden decrease due to stress concentration of the fibre in the laminates. Theoretical models including Rule of Mixture, Halpin-Tsai, Hirsch, and Einstein-Guth models were used to predict the tensile strength of the composites. It was found that the experimental result attained is in close agreement with the values predicted using the rule of mixture model.

1. Introduction

Composites materials are very trendy to be used in structural components. Previous studies proved that mechanical properties of natural fibre reinforced polymer composites are excellent and can be utilized in high-tech applications (Rana et al., 1998). One of the major drawback of natural fibre/polymer laminate is poor adhesion between the hydrophilic natural fibre and hydrophobic polymeric resin. Here, the presence of chemical constituents such as cellulose, lignin, hemicellulose and wax substances in natural fibre prevent them from firmly binding with the polymer resin (Pickering et al., 2016). Hence, an alkaline treatment using sodium hydroxide (NaOH) was introduced to improve the bonding between the matrix and the fibre, by removing the hydrogen bonding of the fibre cellulose (Lee et al., 2009). Interestingly, a study by Bledzki (2008) on the effect of acetylation on the mechanical properties of flax/polypropylene composites found that the treated fibre yield in a decrease in the mechanical properties of the composites, due to degradation of cellulose and fibre cracking (Bledzki et al., 2008). Apart from the hydrophilic of the natural fibre, the effect of fibre content on the composite laminate is undoubtedly significant. Among the factors that can influence the mechanical properties of the composites include fibre orientation, fibre length and weight ratio of the fibre. Several researchers have investigated the influence of fibre loading on the mechanical behaviour of natural fibre composites (Keck and Fulland, 2016). These studies concluded that the tensile strength and Young's Modulus increase up to 50 % with increasing fibre loading. In contrast, Mustapha et al (2015) reported that the effect of volume fractions on grass straw reinforced earth-based matrix offered significantly higher stiffness and strength of the composite structure with some limitations. They suggested that when the fibre content reaches an optimum value, the strength of the structure degraded due to high concentration of the fibre. This study aims to characterize the mechanical behaviour of jute fibre-reinforced polypropylene laminate following tensile test. Following this, the results from analytical models using the Rules of Mixture, Halpin-Tsai's, Hirsch's and Einstein & Guth models are compared with the experimental findings.

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2. Modelling of tensile properties

To predict the tensile strength of the composites, a number of theoretical models including Rule of mixture, Halpin- Tsai, Hirsch's model, Einstein Guth model are employed (Kathirpandian et al., 2016).

a. Rules of Mixture (RoM) Model:

According to RoM model, tensile strength and modulus can be predicted using the equation as expressed in Eq. (1) and (2) respectively:

$$Ec = EfVf + EmVm \quad (1)$$

$$\sigma c = \sigma fVf + \sigma mVm \quad (2)$$

Whereσ_c, σ_m, and σ_f are the tensile strengths of the composite, matrix, and the fibre respectively; E_c, E_m, and E_f are the moduli of composite, matrix, and fibre, respectively; V_m and V_m are the volume fractions of the matrix and fibre.

b. Halpin-Tsai Model:

According to this model, the equations used to predict tensile strength and modulus are as given in Eq (3) and (4) as follows:

$$E_c = E_m \left[\frac{1+\xi\eta V_f}{1-\eta V_f}\right] \quad (3)$$

$$\sigma_c = \sigma_m\left[\frac{1+\xi\eta V_f}{1-\eta V_f}\right] \quad (4)$$

where ξ is the parameter of the geometry which must be in range 0 ≤ ξ ≤ ∞ and also be applied to determine the in-plane shear modulus of a unidirectional composite, ξ is equal to 1 and η is given by Crookston(2004):

$$\eta = \frac{\left(\frac{E_f}{E_m}\right)-1}{\left(\frac{E_f}{E_m}\right)+\xi} \quad (5)$$

c. Hirsch's Model:

According to this model, the equations used to predict tensile strength and modulus are as given in Eq. (6) and (7) below:

$$Ec = x\left[E_f V_f \ + \ E_f V_m\right] + [1-x]\frac{E_f V_m}{E_m V_f + E_f V_m} \quad (6)$$

$$\sigma_C = x\left[\sigma_f V_f \ + \ \sigma_m V_m\right] + [1-x]\frac{\sigma_f V_m}{\sigma_m V_f + \sigma_f V_m} \quad (7)$$

Where *x* is the empirical coefficient of the fibre orientation, fibre length and stress amplification at fibre ends. In the study of mechanical properties for heterogeneous natural fibre composites, Kavelin (2005) indicated that x=0.15 is the reasonable correlation with the experimental data.

d. Einstein and Guth's Model:

According to this model, the predict tensile strength and modulus are expressed in Eq. (8) and (9) below:

$$E_c = E_m\ [1+2.5V_f + 14.1V_f^{\ 2}] \quad (8)$$

$$\sigma_c = \sigma_m\ [1- V_f^{\ 2/3}] \quad (9)$$

Here, the Young's Modulus and tensile strength of the composite depends on the modulus and tensile strength of constituents present in the composite and volume fractions of the fibre and matrix.

3. Material, fabrication and testing procedures

The natural fibre used in this study was of 2/2 twill of woven jute fibre supplied by Easy Composites Ltd. In order to fabricate the fibre reinforced laminated composites, polypropylene film was used. It was supplied by Collano UK. The specimens were manufactured using Gotech hot press machine. The composite laminates were fabricated by layering two plies of jute fibre with the polypropylene films. Here, the laminates with dimensions of 250 mm × 250 mm were fabricated using picture frame steel mold. Prior to that, Teflon sheet was stuck onto the mold surface for easy removal. The lower and upper rigid platens were pre-heated at 130ºC, before the laminate was compressed at 2 bars for 10 min. Following this, the laminates were then left for cooling before removed from the hot press machine. Laminates were then inspected before sectioning for tensile testing following ASTM D3039. The sample dimension is of 25 mm × 25 mm with a gauge length of 150 mm. The ends were also threaded for easy adaptation to the machine grips. This test was carried out using Shimadzu AG-X Testing Machine at a crosshead displacement rate of 1 mm/min. A scanning electron microscope (SEM) Model EVO Carl Zeiss SMT (Carl Zeiss, UK) was used to conduct surface analysis on the fractured samples. Details of the specimens are tabulated in Table 1.

Table 1: Specimen properties of jute-PP composites.

Specimen	Layering sequences (J=jute, PP=polypropylene)	Volume fraction	Thickness (mm)	Mass (g)	Density (g/cm^3)
J1	[J, PP, J]	80	1.67	8.15	1.36
J2	[PP,J,PP,J,pp]	60	1.90	9.90	1.26
J3	[2PP, J, 3PP, J, 2PP]	50	2.17	11.16	1.22
J4	[2PP, J, 4PP, J, 2PP]	40	3.01	13.42	1.16
J5	[2PP, J, 6PP, J, 2PP]	30	3.91	17.35	1.10
J6	[5PP, J, 8PP, J, 5PP]	20	4.57	24.64	1.05

4. Results and discussion

4.1 Tensile test result

Figure 1a shows typical stress-strain traces for the jute-PP laminates. Here, specimens with the highest fibre volume fraction exhibit the highest tensile strength and vice versa. All the five tested specimens have fibre volume fraction between 20 to 80 %. On the other hand, specimens with 50 to 60 % fibre volume fraction point out outstanding performance. Figure 1b suggests that the Young's modulus and tensile strength significantly increased when the fibre volume fraction increased from 20 to 50 %. However, the tensile properties showed a sudden dropped with an increasing fibre volume fraction from 60 % and 80 %.

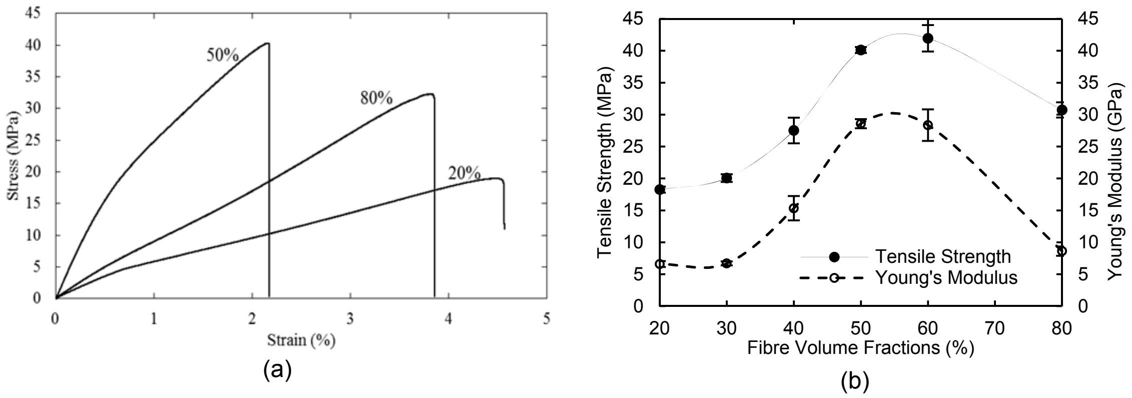


Figure 1: (a) Stress-strain curves for jute-PP tensile specimen with fibre volume fraction of 20 %, 50 % and 80 %. (b) The effect of fibre content on the tensile strength and Young Modulus of jute-PP sandwich laminates

Figure 2 shows the effect of fibre-to-resin content on the tensile strength and Young modulus values of the jute polypropylene composites. From the graph, with an increase in fibre volume fraction, the tensile strength and Young's Modulus reached a maximum value at 50 to 60 % jute-PP composites fibre loading and then decrease slightly when the fibre volume fraction is between 60 to 80 %. Rejab et al. (2008) found that there is a limit to adding fibre volume into the composite laminates to increase the mechanical performance, because excessive amount of fibre would degrade the performance of the composite structure (Rejab et al., 2008). At fibre volume fraction of 50 to 60 %, the specimen reached optimum tensile properties, which suggest that a strong bonding is formed between the fibre and the matrix. This is due to an effective load transfer which depends on the quality of the matrix and fibre bonding (Jauhari et al., 2015). Thus, this indicates that the best fibre volume fraction for the specimen is between 50 and 60 % fibre volume fraction. Moreover, such observation is also supported by a previous study on the effect of fibre loading on the mechanical properties of hybrid composites, which reported that the best mechanical properties is achieved at 52 percent of fibre content (Ozturk, 2010). Nonetheless, with an increasing fibre fraction, i.e. at 80 %, the tensile properties showed significant drop, possibly due to insufficient amount of matrix to bind the fibres together, making them less effective to withstand a large amount of applied load. Variations in the energy absorbed of this laminates with fibre volume fraction is apparent in Figure 2a, showing a gradual decrease in the energy absorption with increasing fibre volume fractions, from 20 % to 30 % fibre volume fractions. However, there is a scatter in the results at fibre loading between 40 and 60 %, which later steadily increase up to 80 % fibre volume fractions. Figure 2b shows the elongation percentage of jute-PP composite laminates when subjected to tensile loading. Highest elongation is reached at the minimum fibre loading of 20 %, which then reduced gradually when fibre loading reaches 50 %, an indication that there is excessive amount of matrix in the laminates. Nonetheless, the percent elongation increased significantly when the fibre loading increase to 80 %, possibly due to the stress concentration of the fibres.

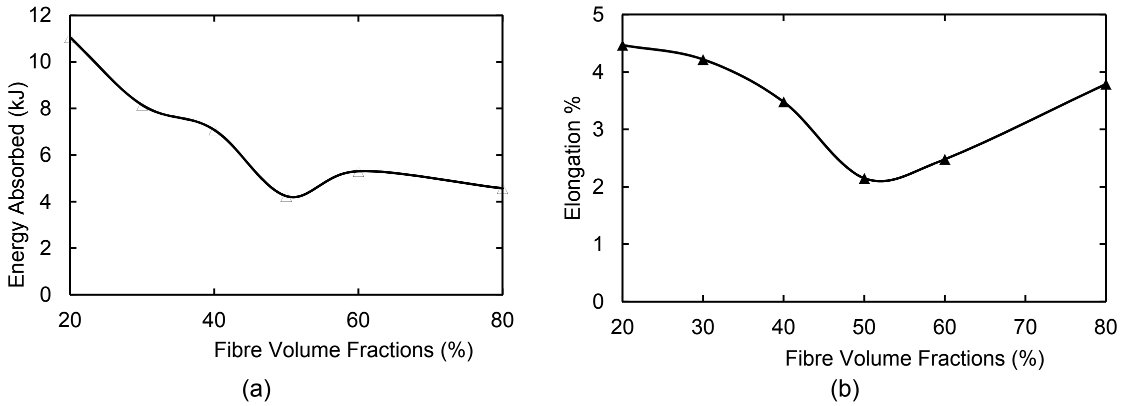


Figure 2: The effect of fibre content on the (a) energy absorption and (b) elongation of jute-PP sandwich laminates

Jute-PP composite laminates fabricated using volume fractions of 20, 30, 40, 50, 60 and 80 % were analysed in this study. However, it is found that composite laminates incorporated with 50 to 60 % volume fraction yield in the highest mechanical properties. Figures 4a and b show comparison between experimental and theoretical values for the tensile strength and Young's Modulus of the composite laminates. Here, the tensile strength and Young's Modulus are predicted using Rules of Mixture. In general, fibre failure strain is lower than the matrix failure strain. In fact, fibres have the same strength; the tensile fibre ruptures determined the rupture in the composites. Therefore, estimation of longitudinal tensile strength could be calculated by using Eq. (1) and (2). These suggest that increasing the fibre length and volume fraction leads to greater difference between the experimental and theoretical values. Figure 3 shows the tensile strength and Young's Modulus of jute-pp composites based on four different models.

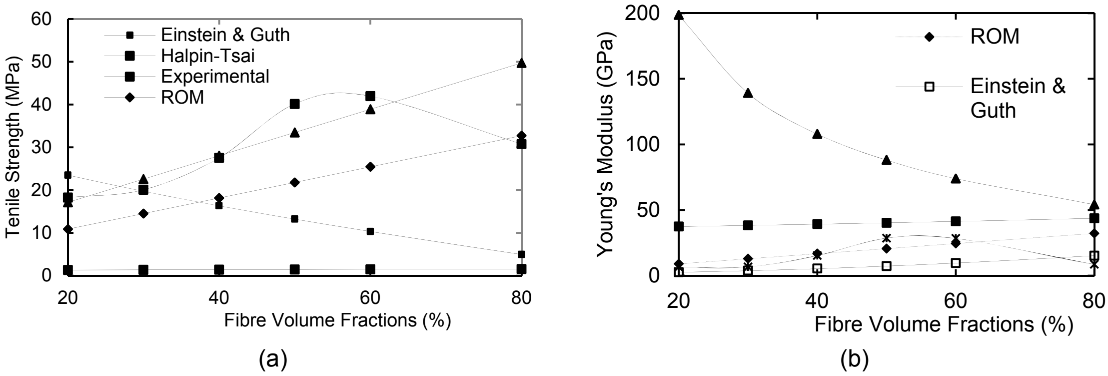


Figure 3: (a) Tensile strength and (b) Young's Modulus of jute-pp composites based on four different models.

When comparing the experimental results with those of the Halpin Tsai model, the tensile strength evaluated using the model exhibit lower tensile strength values but higher Young's Modulus. The values are predicted by using Eqs. (3) and (4). By assuming that the fibres are in closely packed fashion, the value of 'ξ' is taken as 1. Hirsch model is the combination of parallel and series models which are comfortably applicable to the short fibre composites. In this model, parameter x is a controlling factor which describes the behavior of the composite. The value predicted in this model is in better comparison with experiment, in which x is equal to

0.15 in Eqs. (5) and (6). The tensile strength predicted by using Hirsch model is nearest to the experimental results among all the models; nonetheless the largest deviation is found for the Young's Modulus from the experimental data. As can be seen in Einstein and Guth Model in Eqs. (7) and (8), the reinforcement effect is dependent on its geometry, in which only the volume of fraction is considered. However, comparison between experimental and theoretical by using Einstein and Guth model shows that the values predicted are in close proximity with the experimental results in terms of the Young's Modulus.
Correlation study between the experimental and theoretical values of the tensile modulus for the composites with an optimum fibre volume fraction of 50 to 60 % are also studied. Here, there is a good agreement between the tensile strength and Young's Modulus values between those of the predicted and the experimental. Such observations suggest that the critical fibre length and optimum fibre volume fraction plays an important role in predicting the tensile properties of the composite.

4.2 Scanning Electron Microscope

Images of the specimens following tensile testing are shown in Figure 4. The visual observations reveal that the specimens experience fibre pull-out suggested by cup and cone fracture after tested in uniaxial tension. Initially, the tensile load caused the structure to stretch and experience elastic deformation at the peak load, where the structure begins to crack. Increasing applied stress caused the fibre pull-out that made the specimens break and the hairy fibre shows that the specimens undergo fibre pull-out with cup and cone fracture. The breakage occurs nearly 90º to the applied stress with no necking.

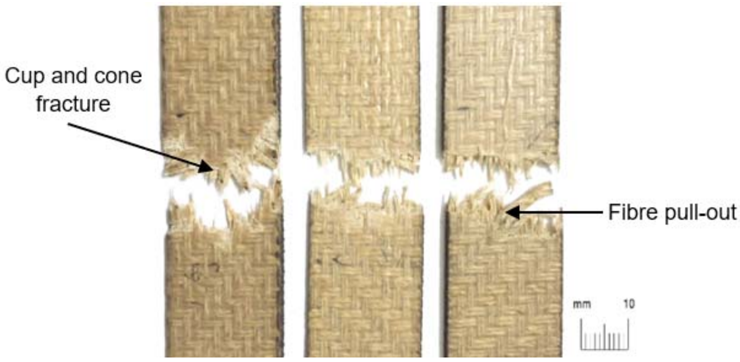
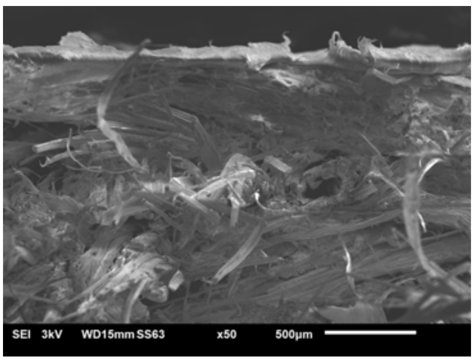
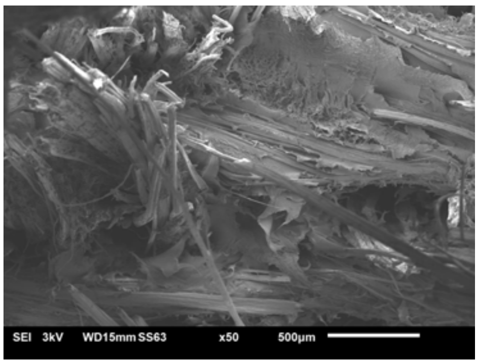


Figure 4: Photo of jute-PP with (a) 20 % (b) 50 % and (c) 80 % of fibre volume fraction.

Figure 5 shows the specimen with different amount of fibre volume fraction.
Figure 5a shows the specimen with the least amount of fibre volume fraction (20 %), giving the lowest tensile strength due to fewer amount of fibre with excessive amount of matrix. On other hand, in Figure 5b, the specimen with fibre volume fraction of 50 % exhibit sufficient binding between the fibres and the PP which yield in the highest tensile properties. Meanwhile, for specimen with the highest fibre loading of 80 %, as given in Figure 5c, insufficient amount of PP in the laminates to wet the fibre attribute to inefficient load transfer, resulting in relatively poor tensile properties.

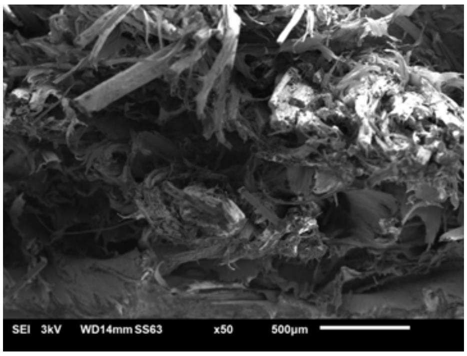


(a)



(b)

Figure 5: SEM micrographs of tensile failure for (a) 20 %, (b) 50 % and (c) 80 %fibre volume fraction.



(c)

Figure 5: SEM micrographs of tensile failure for (a) 20 %, (b) 50 % and (c) 80 %fibre volume fraction.

5. Conclusions

The fibre content has a significant influence on the mechanical properties of composite laminate. Generally, increasing the amount of fibre loading up to an optimum value results in an increase in the tensile strength and Young's Modulus for the composite laminates studied. However, when beyond the optimum fibre volume, the strength of the jute-PP composite laminates decreased, attributed to an excessive amount of the fibres which resulting in inefficient load transfer from the matrix to the fibre in the composite system. The results suggest that an optimum value fibre volume fraction for this type of composites achieved at approximately 60 %. Correlation between the experimental and predicted value from the models employed suggest that there is relatively good agreement between the tensile strength and Young's Modulus obtained experimentally with those of the Rules of mixture results.

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