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Hybrid Effect in the Mechanical Properties of Jute/Rockwool Hybrid Fibres Reinforced Phenol Formaldehyde Composites

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Abstract: This research work was concerned with the evaluation of the effect of fibre content on the mechanical properties of composites. Composites were fabricated using jute/phenol formaldehyde (PF), rockwool/PF, and jute/rockwool hybrid PF with varying fibre loadings. Jute and rockwool fibre reinforced PF composites were fabricated with varying fibre loadings (16, 25, 34, 42, 50, and 60 vol.%). The jute/rockwool hybrid PF composites were manufactured at various ratios of jute/rockwool fibres such as 1:0, 0.92:0.08, 0.82:0.18, 0.70:0.30, 0.54:0.46, 0.28:0.72, and 0:1. Total fibre content of the hybrid composites was 42 vol.%. The results showed that tensile strength of the composite increased with increasing fibre content up to 42 vol.% over which it decreased for jute and rockwool fibre reinforced PF composites. Flexural strength of the composite was noted to peak at a fibre loading of 42 vol.% for jute/PF composites, and 34 vol.% for rockwool/PF composites. Impact strength of jute/PF composites increased with increasing fibre loading but that of rockwool/PF composites decreased at higher (>34 vol.%) fibre loadings. Tensile, flexural, and impact strengths of jute/PF composites were found to be higher than those of rockwool/PF composites. The maximum hardness values were obtained 42 vol.% for jute/PF composite, and 34 vol.% for rockwool/PF composite. Further increase in fibre loading adversely affected the hardness of both composites. For jute/rockwool hybrid PF composites, tensile and impact strengths decreased with increasing rockwool fibre loading. The maximum flexural strength of jute/rockwool hybrid PF composites was obtained at a 0.82:0.18 jute/rockwool fibre ratio while maximum hardness was observed at a 0.28:0.72 jute/rockwool fibre ratio. The fractured surfaces of the composites were analysed using scanning electron microscope in order to have an insight into the failure mechanism and fibre/matrix interface adhesion.

Keywords: Jute fibre, Rockwool fibre, Hybrid composites, Mechanical properties, Phenol formaldehyde

Introduction

Inorganic fibres including glass, rockwool, ceramic, boron currently are used reinforcing materials in fibre reinforced composites. The main reason for the interest in fibre reinforced composites is due to their high specific modulus, high stiffness to weight ratio and high strength to weight ratio compared with conventional materials. However, these materials are quite expensive materials and expecially toxicity to the environment [1-5]. During the last few decades, much effort has been placed on the utilization of natural fibres such as jute, hemp, kenaf, coir, sisal, ramie, and grass as alternatives to inorganic fibres both in thermoplastic and thermosetting composites. These fibres have many advantages over man-made fibres due to low density, low cost, recyclability and biodegradability [6-10]. Moreover, they are renewable and possess relatively high strength and stiffness [11]. Despite the advantages listed above they suffer from some limitations such as lower modulus, poor resistance to moisture absorption [12].

Among all the natural fibre reinforcing materials, jute appears to be a promising material because it is relatively inexpensive and commercially available in the required form. It has higher strength and modulus than plastics and is a good substitute for conventional fibres in many situations [13]. However, the jute fibre has a multicellular structure composed of microfibrils and the cross-section is highly non-uniform. Furthermore the mechanical and physical properties are highly inconsistent and depend on geographic origin, climatic growth conditions and processing techniques [1].

Rockwool, sometimes called stonewool, is a type of inorganic fibre. Rockwool is used primarily for thermal and acoustical insulation, typically in buildings, vehicles and other industrial equipments. It has a high tensile strength and modulus, high chemical resistance, high dimensional stability, and has excellent insulation properties [14].

In literature, extensive research and development have been done to characterize and understand the mechanical performance and physical properties of the fibre reinforced thermosets and thermoplastic composites. The most commonly used thermoset resins are polyester, epoxies, and phenol formaldehyde resin (PF). Comparatively, few works have been reported on thermoset resins among which only few dealed with phenolic thermoset resins despite their extensive use. As one of the most important thermosetting polymers, PF resin exhibits desired properties including high stiffness, electrically good insulating property, dimensional stability and excellent chemical corrosion resistance however, it suffers from brittleness. Recently many studies on the reinforcement have been carried out [15,16].

In past decades, three general strategies for the preparation of fibre reinforced composites have been developed. The first and most general strategy for the preparation of a fibre

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reinforced composite is that the polymer is directly mixed with the fibre. The second strategy involves the grafting polymerization of monomers on the surface of fibre. The third strategy is the reinforcement by two or more fibres in a single matrix which is called hybrid composites [15]. Research revealed that the behavior of hybrid composites appears to be simply a weighted sum of the individual components in which there is a more favorable balance between the advantages and disadvantages inherent to any composite material. It is generally accepted that the properties of a hybrid composite are controlled by factors such as inherent properties of matrix (nature, length, and relative composition of the reinforcements), fibre-matrix interface, and hybrid design, etc [17,18].

In the present study, a detailed investigation was carried out on the mechanical performance of the jute/PF, rockwool/PF, and jute/rockwool hybrid PF composites. Tensile and flexural properties such as stress-strain behaviour, strength, flexural modulus, and elongation at break of composites as a function of fibre content were analysed. The tensile fracture mechanism of the composites was also studied by scanning electron microscopy (SEM). Impact fracture mechanisms were evaluated using SEM. Variations in hardness, density and void of the composites with various fibre volume contents were also checked.

Experimental

Materials

Phenol formaldehyde novalac type resin, used as matrix material, was supplied by the Cukurova Ltd. Manisa, Turkey. The basic properties of the resin were given in Table 1 [19]. Jute and rockwool were used as reinforcing fibres. Jute was obtained from Bangladesh Jute Research Institute (BJRI) and was cut to lengths of 5-10 mm. It comprises of (59-61 %) cellulose, (15-17 %) pentosan, (12.5-13.5 %) lignin, (4.8-5.2 %) polyuronide, (2.8-3.5 %) acetyl value, (0.9-1.4 %) fat, (1.56-1.87 %) nitrogenous matter and (0.5-0.79 %) mineral substances. Rockwool fibre was obtained from Izocam Company, Kocaeli, Turkey. An approximate chemical analysis of rockwool fibre is 45 % SiO_2, 12 % Al_2O_3, 11 % MgO, 10 % Fe_2O_3, 9 % CaO, 2.5 % TiO_2, 2 % Na_2O, 1.5 % K_2O and traces. Important physical and mechanical properties of jute and rockwool fibres are given in Table 2 [14,20,21]. The SEM micrographs of jute and rockwool fibres are shown in Figure 1(a) and (b).

Table 1. Physical and mechanical properties of phenol formaldehyde novalac type resin

Density (g/cm^3)	1.27
Tensile strength (MPa)	34-62
Elongation at break (%)	0-2
E-modulus (GPa)	2.8
Melting point (^{o}C)	90
Powder size (μm)	45

Table 2. Physical and mechanical properties of jute and rockwool fibres

Fibre	Density (g/cm^3)	Tensile strength (MPa)	E-modulus (GPa)	Elongation at break (%)	Diameter (μm)
Jute	1.46	500-800	10-30	1.8	10-40
Rockwool	2.70	352-700	45-81	0.8	8-20

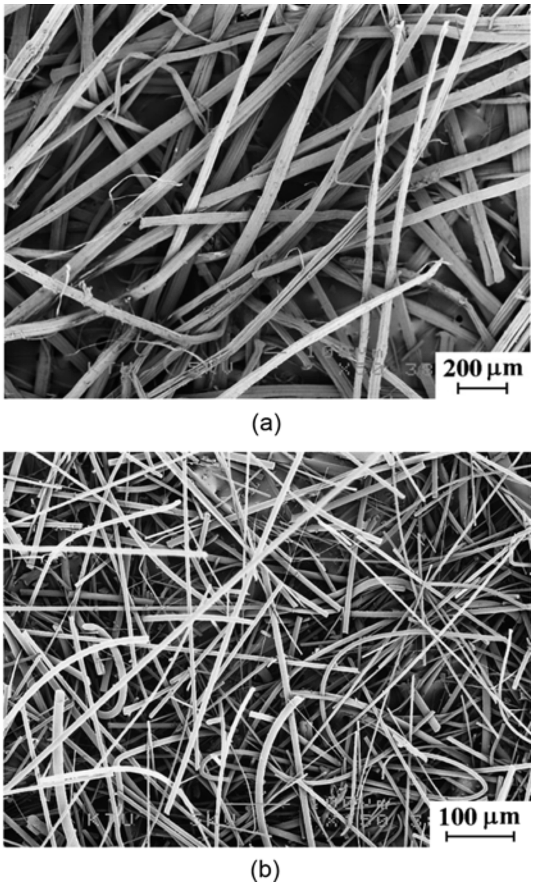


Figure 1. SEM micrographs of fibres; (a) jute and (b) rockwool.

Preparation of Composites

The components of composites were weighed with sensitivity of 1 mg and mixed for 4 min in a finned type mixer. The mixture was loaded into a steel mould and then hot-pressed at 120 ^{o}C and 15 MPa for 15 min. Test samples were cut from composite sheets. At least five samples have been taken for each test to obtain average value. All mechanical tests were performed at room temperature. Jute/PF composites and rockwool/PF composites having various fibre loadings from 16 to 60 vol.% were prepared and tested. Total fibre loading of the hybrid composites was fixed at 42 vol.%. Hybrid composites containing different volume ratios of jute/rockwool fibre such as 1:0, 0.92:0.08, 0.82:0.18, 0.70:0.30, 0.54:0.46, 0.28:0.72, and 0:1 were also tested.

Analysis of Mechanical Properties of Composites

Tensile Test

The tensile test was conducted on a Instron 3382 universal testing machine equipped with non-contacting video extensometer according to ASTM D638-03 standart. The test was carried out at the constant strain rate of 5 mm/min.

Flexural Test

The flexural test of samples was performed Instron 5569 universal testing machine. The three-point bend flexural test was conducted in accordance with ASTM D790-07 standard. The flexural strength was calculated using the following equation;

$$\sigma_f = \frac{3PL}{2bd^2} \tag{1}$$

Where σ_f is the flexural strength, P is the maximum applied load, L is the length of support span, b and d are the width and thickness of the samples, respectively.

Impact Test

The charpy impact tests were done on a Frank impact tester according to ASTM D256-06 standard. All the test samples were un-notched. Impact loading was done with a 7.5 J hammer. The impact strength was calculated by dividing the absorbed impact energy recorded by the cross-sectional area of the sample.

Rockwell Hardness

The hardness of the samples was measured using a rockwell hardness testing machine according to ASTM D785-03 standard in M scale. In this scale, the diameter of hard steel ball indenter is 6.35 mm, and the minor and major loads are 10 and 100 kg, respectively.

Density

The density of the composites was determined in accordance with ASTM D792-00 standard. The density measurements were carried out by determining weight of the sample in air (m_A) and then in the liquid (m_L) i.e., weighing the sample in the bucket submerged in the liquid. The density was then calculated using the formula;

$$\rho_S = \rho_L \frac{m_A}{m_A - m_L} \tag{2}$$

where ρ_S is density of the sample and ρ_L is density of the liquid.

Morphology of Fracture Surface

Jute fibre, rockwool fibre and micrographs of the fractured surfaces of the composites were studied by a scanning electron microscope, Jeol JSM 6400 at 5 keV. The fractured portions of the samples were cut and the SEM micrographs were taken. Uniform gold coating of the samples prior to SEM analysis was performed in order to make the surface conducting. Micrographs of the fractured portions were taken under different magnifications. The tensile and impact micrographs of the composites were taken to study the fracture mechanisms and interface adhesion of the composites.

Results and Discussion

Tensile Properties

The tensile strength of jute fibre/PF composites at different fibre loadings is shown in Figure 2. It can be clearly seen that the tensile strength of the samples increases with increasing jute fibre loading up to 42 vol.% above which it decreases. The range of the tensile strength was between 32.18-81.34 MPa for 16-60 vol.% fibre loadings in the current work. The tensile strain was between 1.65-3.12 % at the same loadings. The maximum tensile stress value of the composites was 81.34 MPa for 42 vol.% fibre loading. On the other hand, the tensile strain of the composites increased with jute fibre loading. The tensile strength of a composite material is mainly dependent on the strength and modulus of fibres, the strength and chemical stability of the matrix and the effectiveness of the bonding strength between matrix and fibres in transferring stress across the interface [1]. When fibre reinforced composites are subjected to load, the fibres act as carriers of load and stress is transferred from the matrix along the fibres leading to effective and uniform stress distribution, which results in a composite having good mechanical properties [22]. At low levels of fibre loading (16 vol.%), the matrix is not restrained by enough fibres causing the bond between matrix and fibre to break, leaving the matrix diluted by non-reinforcing debonded fibres [15]. As the fibre loading increases (i.e. at 42 vol.%), the stress is more evenly distributed and the composite strength increases. But with the further addition (i.e. to 60 vol.%), the

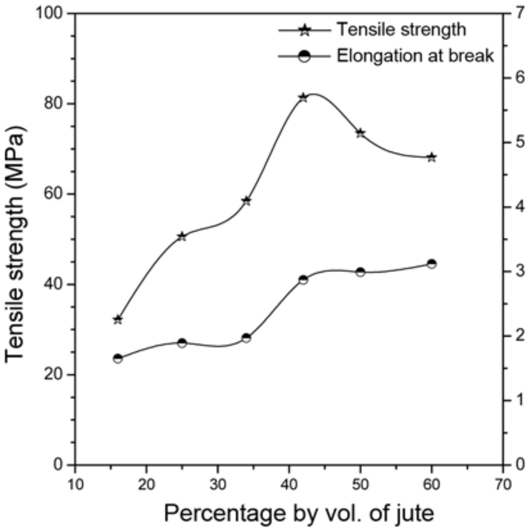


Figure 2. Effect of jute fibre loading on the tensile properties of jute/PF composite.

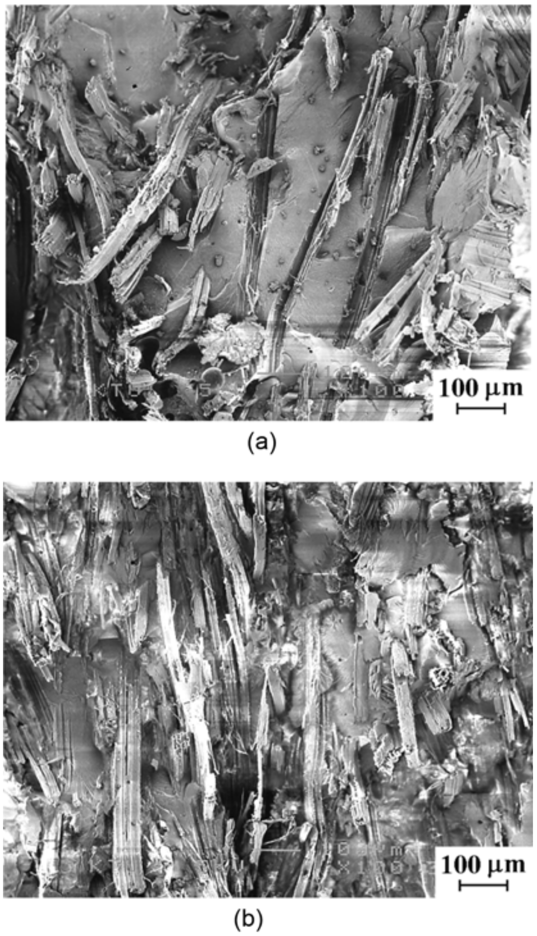


Figure 3. SEM micrographs of tensile fractured surfaces of jute/PF composites; (a) fibre loading 16 vol.% and (b) fibre loading 42 vol.%.

process is difficult and the dispersion becomes very poor with the resultant deterioration in properties [18].

SEM micrographs of the tensile fractured surfaces of jute/PF composites containing 16 and 42 vol.% fibre loadings are shown in Figure 3(a) and (b). Usually, in natural fibre reinforced composites, the predominant failure mechanism is fibre breakage since there is a strong interaction between fibres and phenolic resin due to hydrophilic nature of cellulose and PF resin. So the debonding of fibre from matrix is difficult and fibre pull out is less in natural fibre/PF system [23]. However, along with increasing fibre loading, jute fibres are broken without a complete pull out during the fracture process and there is much PF matrix coating the fibres. It is also noted that the fibres are failed by tearing, but no complete interfacial failure is observed, indicating that there is very good adhesion in the jute/PF system (see Figure 3(a) and (b)).

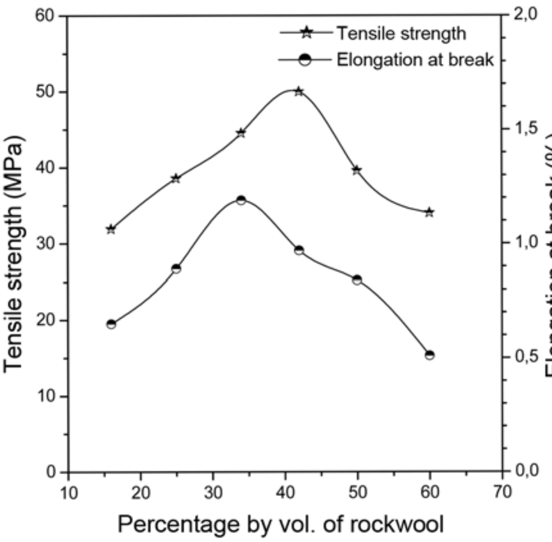


Figure 4. Effect of rockwool fibre loading on the tensile properties of rockwool/PF composite.

Figure 4 shows the variation of tensile strength and elongation at break for rockwool fibre loading in rockwool/PF composites. The tensile strength of rockwool/PF composite increased with increasing rockwool fibre loading up to 42 vol.%. The maximum tensile stress value of the composites was 49.98 MPa. Above this loading, the tensile strength decreased. This is probably due to the lost of integrity of the matrix and insufficient wetting between fibre and matrix as a result of high fibre loading. However, elongation at break also increased as rockwool fibre loading increased to 34 vol.%. At higher loadings, a reverse trend was observed.

Higher strength values were expected considering the strength of the rockwool fibre itself compared to jute fibre itself. The relatively low strength may be due to weak interfacial shear strength between inorganic rockwool fibre and PF matrix. This is illustrated in SEM images (Figure 5(a) and (b)) which show fibre-PF matrix debonding and clean fibre surfaces. As can be seen in Figure 5(a) and (b), the surfaces of the rockwool fibres are quite smooth, there is no evidence or trace of any matrix resin adhering to the rockwool fibres and well-defined holes of pulled out fibres could be observed. The distribution of the rockwool fibres is uniform throughout the polymer matrix. Considerable fibre pull out is also visible in the fracture surface of the composites containing 16 and 42 vol.% rockwool fibres.

The hybrid effect of jute and rockwool fibres on the tensile strength and elongation at break of jute/rockwool hybrid PF composite at 42 vol.% fibre loading is presented in Figure 6. Tensile strength and elongation at break values of the hybrid composite at 0.08 volume fraction of rockwool fibre were 79.65 MPa and 2.63 %, respectively. Corresponding values at 0.72 volume fraction were 51.08 MPa and 1.56 %, respectively. In a hybrid composite, the occurrence of a hybrid effect (negative or positive) of the composite are mainly dependent on the strength and elongation at break of the individual reinforcing fibres and relative volume fraction

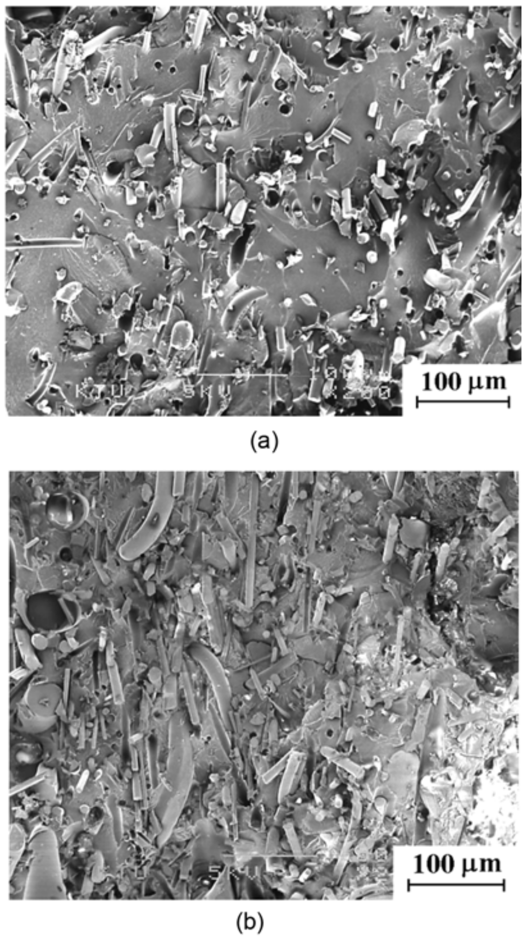


Figure 5. SEM micrographs of tensile fractured surfaces of rockwool/PF composites; (a) fibre loading 16 vol.% and (b) fibre loading 42 vol.%.

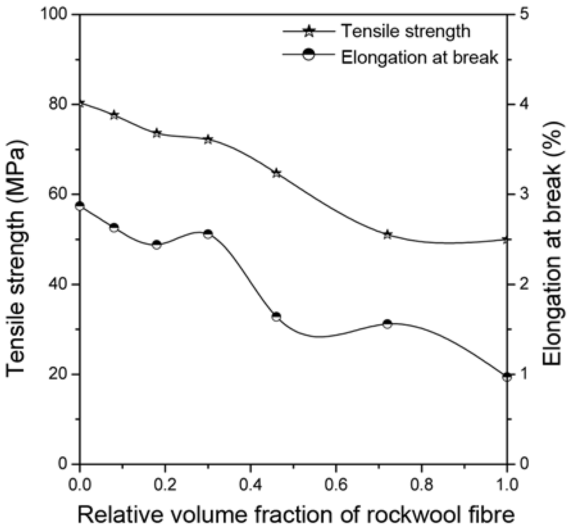


Figure 6. Variations in tensile properties of jute/rockwool hybrid PF composites with relative volume fractions of jute and rockwool fibre (total fibre loading of the composite; 42 vol.%).

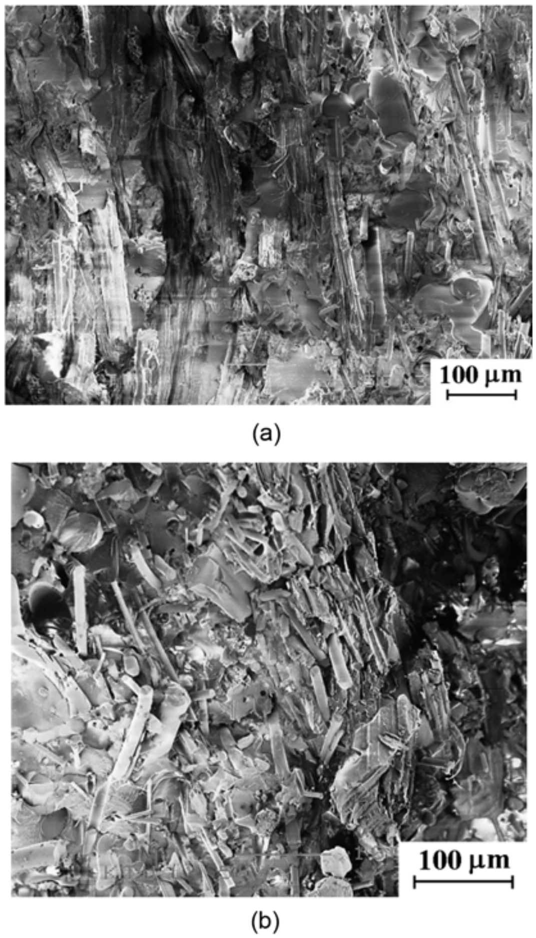


Figure 7. SEM micrographs of tensile fractured surfaces of jute/rockwool hybrid PF composites; (a) jute/rockwool ratio 0.92:0.08 and (b) jute/rockwool ratio 0.28:0.72.

of the fibres [17]. As can be seen from Figure 6, increasing volume fraction of rockwool fibre resulted in negative effect on tensile properties of jute fibre, but, the higher values were found compared with rockwool/PF composite. The strength and elongation at break of jute fibre were higher than those of the rockwool fibre (see Table 2). This suggests that the tensile properties of jute/rockwool hybrid PF composite are controlled by the volume of jute fibre rather than rockwool fibre.

Figure 7(a) and (b) show the tensile fractured surface of jute/rockwool hybrid PF composites at different jute/rockwool ratios. As shown in Figure 7(a), the composite had only a small amount of rockwool fibre, and it behaves similar to the composite that contains a single type of jute fibre. Therefore, there was a good adhesion at 0.08 volume fraction of rockwool fibre for which prominent fracture mechanism was fibre fracture. As shown in Figure 7(b), as the rockwool fibre content increased, the fracture mechanism changed. Thus, the composite failure at 0.72 volume fraction of rockwool fibre was mainly fibre pull out.

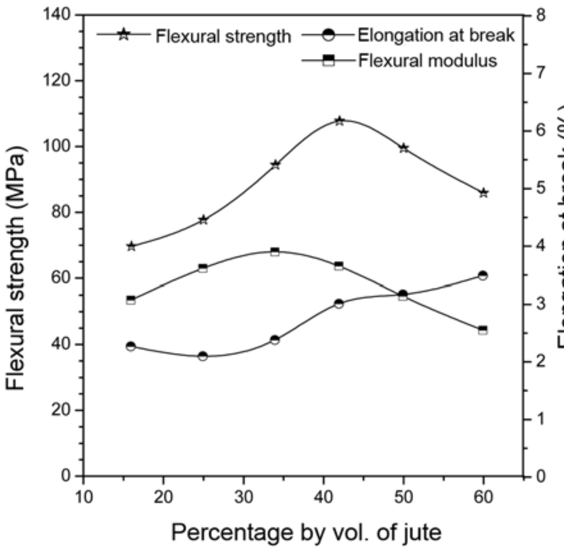


Figure 8. Effect of jute fibre loading on the flexural properties of jute/PF composite.

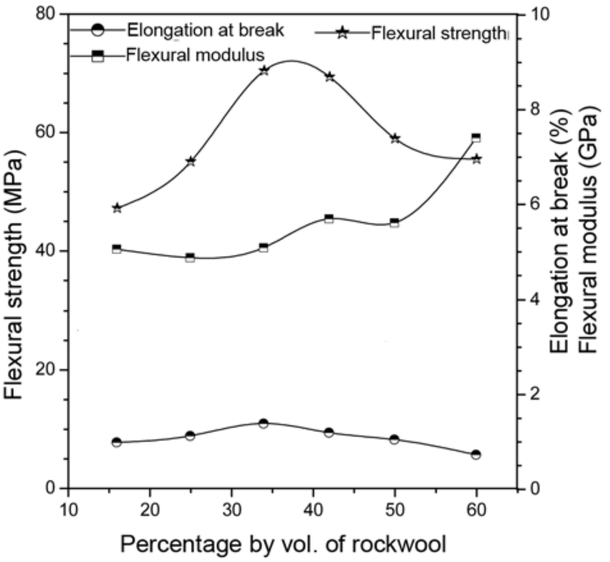


Figure 9. Effect of rockwool fibre loading on the flexural properties of rockwool/PF composite.

Flexural Properties

The flexural properties of jute fibre/PF composites at different fibre loadings is shown in Figure 8. Flexural strength is a combination of the tensile and compressive strengths, and varies with the interfacial shear strength between the fibre and matrix. Flexural testing various mechanisms such as tension, compression, shearing etc. will take place simultaneously [18]. In order to achive effective fiber reinforcement, interfacial strength between the fibre and matrix is the most essential factor. For a composite to be an effective load bearing system, the fibres and matrix must cooperate. This cooperation between the fibres and the matrix will not exist without the presence of the interface. The interfacial strength depends on the surface topology of the fibre. The interface acts as a binder and transfers load between the matrix and the reinforcing fibres. The interfacial area plays a major role in determining the strength of composite material because each fibre forms an individual interface with the matrix. Interfacial bonding is a result of good wetting of the fibres by the PF matrix as well as the formation of a chemical bond between the fibre surface and the PF matrix [2]. It was observed from Figure 8 that the flexural strength and modulus of jute/PF composite increased with increasing jute fibre loading up to 42 and 34 vol.%. respectively. However, elongation at break increased at all fibre loadings. The maximum flexural stress and modulus values of the composites were 107.75 MPa and 3.9 GPa respectively. The increase in flexural strength at ≤42 vol.% could be attributed to the increased resistance to shearing. However, at higher loadings (>42 vol.%) the increased population of fibres could have led to agglomeration, which led to partially blocked stress transfer resulting in lowering of flexural strength.

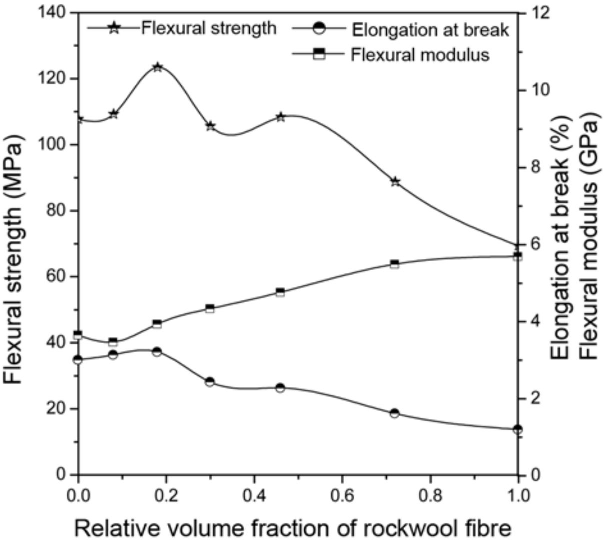


Figure 10. Variations in flexural properties of jute/rockwool hybrid PF composites with relative volume fractions of jute and rockwool fibre (total fibre loading of the composite; 42 vol.%).

The flexural strength of rockwool fibre/PF composites at different fibre loadings is shown in Figure 9. As can be seen from figure, both flexural strength and elongation at break of rockwool/PF composites increased up to 34 vol.% rockwool fibre loading. On the other hand, the flexural modulus increased at all fibre loading. Especially, the composite containing 60 vol.% rockwool fibre showed the maximum flexural modulus and the value was 7.4 GPa. The flexural strength and elongation at break values at 16, 34, and 60 vol.% fibre loadings were 47.22, 70.44, and 55.54 MPa and 0.99, 1.39, and 0.73 %, respectively. The flexural strength and elongation at break of the jute fibre containing composites were higher than those of the rockwool fibre containing composites but flexural modulus was lower at the same loadings.

The incorporation of rockwool fibre at a 0.18 relative volume fraction leads to hybrid composites having a superior flexural strength and elongation. The maximum flexural strength and elongation at break value of the composite were 123.46 MPa and 3.22 %, respectively. The flexural modulus increased with increasing relative volume fraction of rockwool fibre and the highest flexural modulus was obtained at a 1.00 relative volume fraction of rockwool fibre (Figure 10).

Impact Properties

The relationship between fibre loading and impact strength is shown in Figure 11. The impact property of a material shows its capacity to absorb and dissipate energies under impact or shock loading. The impact energy level of the composites depends upon several factors such as the nature of the constituents, construction and geometry of the composites, fibre arrangement, fibre/matrix adhesion, and test conditions. The matrix fracture, fibre matrix debonding, fibre breakage and fibre pull out are important modes of failure in the fibre composites due to impact loading. The applied load, transferred by shear to the fibres, may exceed the fibre/matrix interfacial bond, and debonding may occur. The frictional force along the interface may transfer the stress to the debonded fibre. If the fibre stress level exceeds the fibre strength, fibres may breakage. The breakaged fibres may be pulled out of the matrix, and this involves energy dissipation [24-26]. The impact strength of jute/PF composite was found to increase with jute fibre loading up to 50 vol.%. However further increase in fibre loading above this value caused a moderate decrease in impact strength. These results suggest that the fibre is capable of absorbing energy because of strong interfacial bonding between the fibre and matrix up to 50 vol.% fibre loading. But at higher loadings (>50 vol.%) the inter fibre interaction decreases the effective stress transfer between the fibre and matrix. This contributes to a decrease in impact properties at higher fibre loadings. The impact strength of the jute/PF composite at 16 and 50 vol.% jute fibre loadings was found to be 11.46 and 21.61 kJ/m^2, respectively. The impact strength of rockwool/PF composite increased rockwool fibre contents up to 34 vol.% and then decreased. The maximum impact strength for rockwool/PF composites was 7.6 kJ/m^2 (Figure 11).

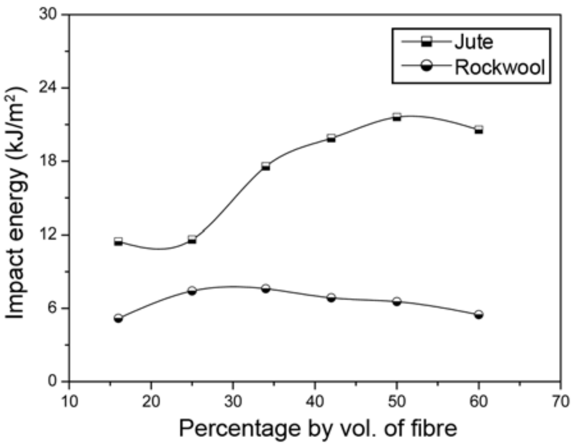
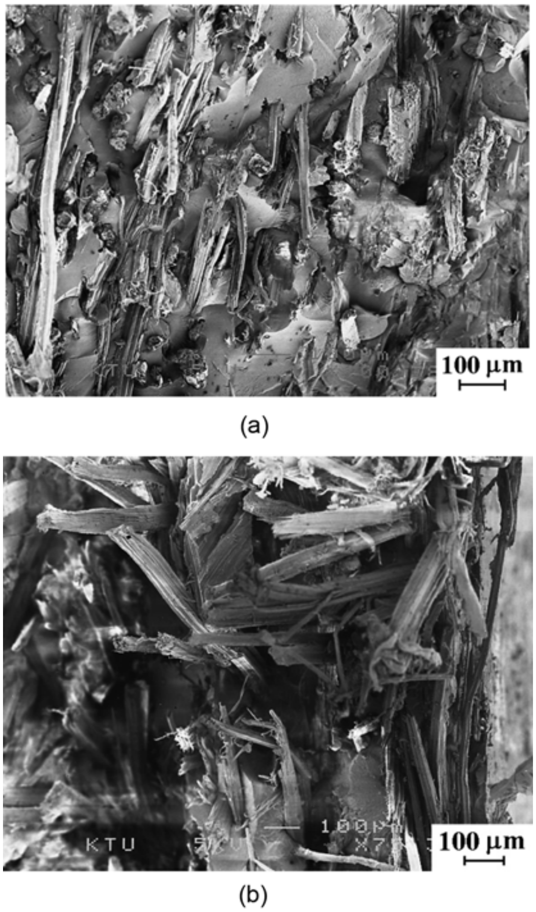


Figure 11. Effect of jute and rockwool fibre loading on the impact strength of jute/PF and rockwool/PF composite.

Figure 12(a) and (b) are SEM micrographs of the impact failure surfaces of jute/PF composites at 25 and 50 vol.% fibre loading. As presented in Figure 12, jute fibres adhered well to the PF matrix and the prominent fracture mechanism is considered mainly fibre breakage. As a result, the composite seemed to fracture in a ductile mode.

SEM micrographs of the impact failure surfaces of rockwool/PF composites at 34 and 60 vol.% fibre loadings are shown in Figure 13(a) and (b). When examining the impact fracture surfaces of rockwool/PF composites, there was poor interaction between rockwool fibres and PF



(a)

(b)

Figure 12. SEM micrographs of impact fractured surfaces of jute/PF composites; (a) fibre loading 25 vol.% and (b) fibre loading 50 vol.%.

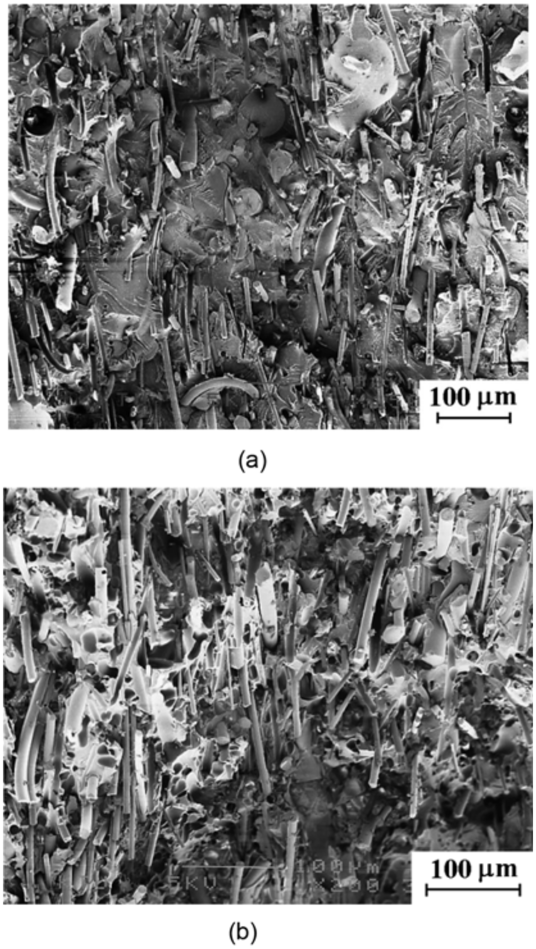


Figure 13. SEM micrographs of impact fractured surfaces of rockwool/PF composites; (a) fibre loading 34 vol.% and (b) fibre loading 60 vol.%.

matrix, surface smoothness, regular cross section and pulled out of rockwool fibres (Figure 13(a) and (b)). Predominant fracture mechanism was fibre pull out and the composite seemed to fracture in a brittle mode.

Figure 14 illustrates the impact strength of jute/rockwool hybrid PF composite. As can be seen, impact energy decreased with increasing volume fraction of rockwool fibre. This decrease was sharp at 0.18 relative volume fraction of rockwool fibre. The impact strength of jute fibre at 42 vol.% loading was found to be 19.88 kJ/m^2. The impact strength values were 13.06 and 7.05 kJ/m^2 for 8 and 72 vol.% rockwool fibre loadings, respectively. The energy dissipated by composite fracture is higher in jute/rockwool ratio of 0.92:0.08 than 0.28:0.72 because of higher volume fraction of jute fibre in hybrid composite.

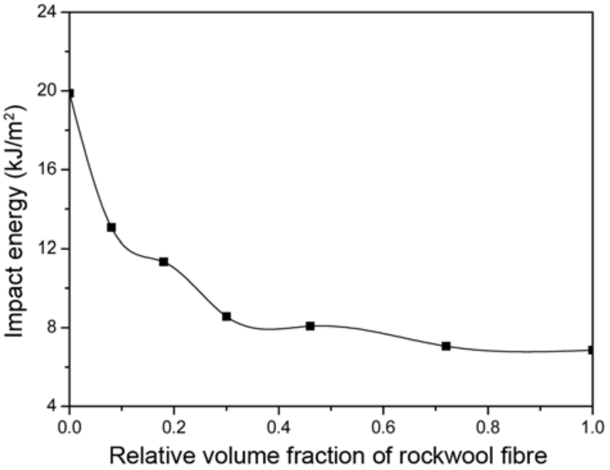


Figure 14. Charpy impact strength versus rockwool fibre volume fractions for jute/rockwool hybrid PF composites (total fibre loading of the composite; 42 vol.%).

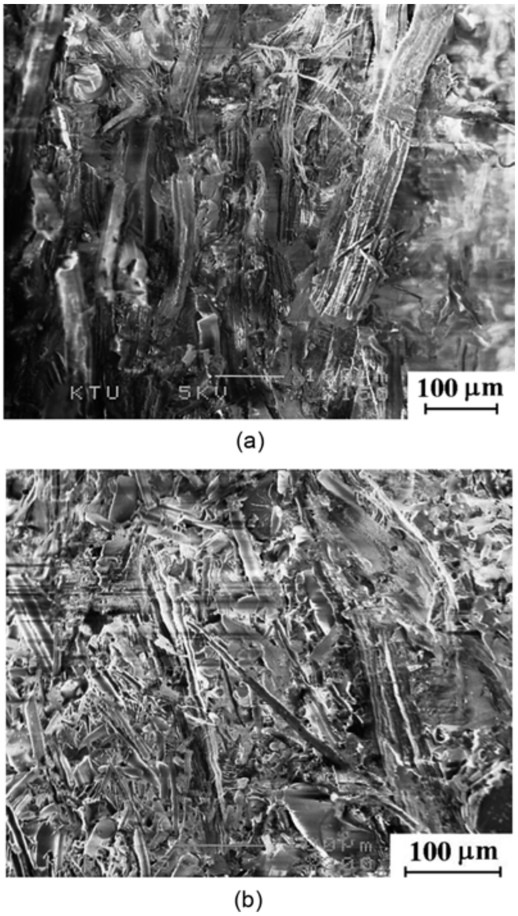


Figure 15. SEM micrographs of impact fractured surfaces of jute/rockwool hybrid PF composites; (a) jute/rockwool ratio 0.92:0.08 and (b) jute/rockwool ratio 0.28:0.72.

Figure 15(a) and (b) present SEM micrographs of impact fractured surfaces of jute/rockwool hybrid PF composites at different jute/rockwool ratios. When examining the impact fractured surfaces of jute/rockwool hybrid PF composites, mainly fibre breakage and little fibre pull out (Figure 15(a)) and chiefly fibre pull out (Figure 15(b)) can be seen.

Table 3. Hardness and density values of rockwool, jute and jute/rockwool hibrid PF composites (total fibre loading; 42 vol.%)

Composite	Composition	Hardness (HRM)	Density theoretical (g/cm^3)	Density experimental (g/cm^3)	Void content (vol.%)
Rockwool/PF	16	107.84	1.50	1.48	1.33
	25	111.98	1.63	1.59	2.45
	34	113.72	1.76	1.72	2.27
	42	111.21	1.87	1.82	2.67
	50	102.86	1.99	1.86	6.53
	60	101.45	2.13	2.01	5.63
Jute/PF	16	86.51	1.30	1.28	1.53
	25	90.99	1.32	1.27	3.78
	34	88.01	1.33	1.30	2.25
	42	98.13	1.35	1.32	2.22
	50	81.56	1.37	1.31	4.38
	60	79.63	1.38	1.29	6.52
Jute/Rockwool/PF	1/0	98.13	1.35	1.32	2.22
	0.92:0.08	96.08	1.39	1.40	0
	0.82:0.18	103.10	1.44	1.42	1.39
	0.70:0.30	103.61	1.51	1.48	1.99
	0.54:0.46	109.20	1.59	1.60	0
	0.28:0.72	113.06	1.72	1.69	1.74
	0/1	111.21	1.87	1.82	2.67

Hardness, Density and Void Formation

Table 3 shows hardness, density and void content of the composites. These properties are interrelated [18]. The hardness values of the rockwool and jute reinforced composites (no hybrid) increased at fibre loadings up to about 40 vol.%. At >40 vol.%, the processing may be difficult due to fibre agglomeration leading to void formation inside the composite. This adversely affects the composite performance.

The void content was calculated using the equation;

$$V = 100(\rho_T - \rho_S)/\rho_T \tag{3}$$

where ρ_T is given by theoretical sample density, ρ_S is measured sample density (see equation (2)) and V is the void content.

Composites at fibre loadings higher than 50 vol.% had more voids (Table 3). Voids in polymer composites is largely attributed to the processing effect which may arise from various sources such as volatiles arising during curing of the resin, residual solvents and entrapped air. Shrinkage during curing of the resin and the cooling rate play also an important role in void formation. The presence of voids is detrimental to the mechanical properties of the composites [18]. The hardness and void content values of rockwool/PF composites at 34, 42, and 60 vol.% rockwool fibre loadings were 113.72, 111.21, and 101.45 HRM, 2.27, 2.67, and 5.63 vol.%, respectively. The same trend is observed jute/PF composites for hardness and void content values. These values of jute/PF composites at 34, 42, and 60 vol.% jute fibre loadings were 88.01, 98.13, and 79.63 HRM, 2.25, 2.22, and 6.52 vol.% respectively. The hardness of rockwool fibre reinforced composites was higher compared to the jute ones at the same fibre ratio. This can be attributed to higher hardness of inorganic fibres than that of natural fibres.

The hardness values of jute/rockwool hybrid PF composites increase with increasing relative volume fraction of rockwool fibre. The maximum hardness value was obtained for 0.28:0.72 jute/rockwool hybrid PF composite and this value was 113.06 HRM. The void content of the composite was 1.74 vol.%.

Conlusion

In this work, mechanical properties of jute/PF, rockwool/PF and jute/rockwool hybrid PF composites were investigated. The tensile, flexural stress-strain, and flexural modulus characteristics of the composites as a function of fibre content were analysed. Impact fracture mechanisms were evaluated. Variations in hardness, density and void of the composites with various fibre volume contents were also checked. The following conclusion drawn:

1. The tensile and flexural strengths of jute/PF and rockwool/PF composites improve by increasing fibre loading up to 42 vol.% and decrease at higher loadings. However, the maximum impact strength occurs at fibre loading of 50 and 34 vol.% for jute/PF and rockwool/PF composites, respectively.
2. Addition of rockwool fibre decreases the tensile and impact properties of jute/rockwool hybrid PF composites while it increases the flexural properties of the composites. For the jute/rockwool hybrid PF composites, the highest performance for strength and elongation is obtained at a

ratio of 0.72:0.18 jute/rockwool hybrid PF composite.

3. The tensile, flexural, and impact strength of jute/PF composites are higher than these of rockwool/PF composites at the same fibre loading.
4. The hardness peaks at a particular fibre loadings at 42 vol.% for jute/PF composite, 34 vol.% for rockwool/PF composite and 0.28:0.72 for jute/rockwool hybrid PF composite.
5. Porosity of the composites increases with fibre content.

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