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Long jute fiber-reinforced polypropylene composite: Effects of jute fiber bundle and glass fiber hybridization

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ABSTRACT: Two types of long jute fiber pellet consisting of twisted-jute yarn (LFT-JF/PP) and untwisted-jute yarn (UT-JF/PP) pellets are used to prepare jute fiber–reinforced polypropylene (JF/PP) composites. The mechanical properties of both long fiber composites are compared with that of re-pelletized pellet (RP-JF/PP) of LFT-JF/PP pellet, which is re-compounded by extrusion compounding. High stiffness and high impact strength of JF/PP composites are as a result of using long fiber. However, the longer fiber bundle consequently affects the distribution of jute fiber. The incorporation of 10 wt % glass fibers is found to improve mechanical properties of JF/PP composites. Increasing mechanical properties of hybrid composites is dependent on the type of JF/PP pellets, which directly affect the fiber length and fiber orientation of glass fiber within hybrid composites. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2015**, *132*, 41819.

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INTRODUCTION

Short fiber-reinforced polymer (SFRP) composites have been widely used for several decades and their market share is continuously growing in several applications such as automobiles, machine parts, durable consumer items, sporting goods, and electrical industrial. The SFRP composites usually made of glass fibers reinforced polymer matrix have played a dominant role in various applications due to their high mechanical properties. However, usage and disposal of glass fiber-reinforced polymer composite have been becoming critical because of their nonbiodegradability. Concern about disposal and recycling has led to renew the interest in renewable and biodegradable materials. As a result, new types of composites based on natural fibers have been developed in recent years. Since the 1990s, natural fiber composites are emerging as realistic alternative materials to glass fiber-reinforced polymer composites in many applications. One of the largest areas of recent growth in natural fiber-reinforced polymer composites is the automotive industry, where the natural fibers are advantageously used as a result of their low density and increasing environmental awareness. Furthermore, the cost saving due to the relatively low cost of natural fibers and the advantages of being nonabrasive to the molding equipment are benefits that to be used in several applications. Natural fiber composites are also claimed to offer environmental advantages such as reduced dependence on nonrenewable resources, lower pollutant emissions, lower greenhouse gas emissions, enhanced energy recovery, and end of life biodegradability of components. Several articles reported that the life cycle assessment studies comparing the using of natural fiber and synthetic fiber in composite materials. Natural fibers production results in lower environmental impacts, reduces the amount of more polluting base polymer matrices, improves fuel efficiency, and end of life incineration of natural fibers results in energy and carbon credit.[1–6] Furthermore, the rising concern toward environmental issues has led to increasing interest in fully green composites. These fully green composites consist of biodegradable polymer matrix and natural fibers. Many research works reported the applications of green composites. Several matrix materials deriving from renewable resources may well represent promising materials for application in green composites. At end of their life, they can be easily disposed of or composted without harming the environment. However, due to the molding methods, bio-based polymer matrices is, generally, made by uncompetitive price, which makes them unaffordable even for large-scale productions. The challenges still exist in the development of more suitable cost-effective fabrication techniques as well as composites having superior mechanical properties using natural fibers as reinforcement.[7–9]

To use natural fibers with commodity thermoplastics, it is necessary to improve the adhesion bonding between fiber and

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Table I. Properties and Price of Polypropylene, Glass Fiber and Jute Fiber

Materials	Density (gcm^{-3})	Price (USDkg^{-1})	Tensile modulus (GPa)	Tensile strength (MPa)
Polypropylene	0.9–1.16	1.65	1.1–1.6	30–40
Glass fiber	2.55	2	70–73	2000–3500
Jute fiber	1.3–1.49	0.925	13–26.5	393–800

matrix because most of hydrophilic natural fibers are incompatible with hydrophobic thermoplastic matrices. This may also result in nonuniform dispersion of fibers within the matrix. In order to improve the affinity and adhesion between reinforcements and thermoplastic matrices in production, chemical coupling agents have to be employed. Chemical coupling agents are used in small quantities to treat surface in such a way that increased bonding between treated surface and matrices. A number of recent papers exist regarding the use of coupling agents for natural fiber-reinforced thermoplastic composites. The results are quite variable, depending on the polymer matrix used, fiber type and quantity, the type of coupling agent used, and processing techniques.[10–13] Another primary drawback of the use of natural fibers is the low-processing temperature required. Their high moisture sensitivity also leads to severe reduction in mechanical properties and may results in the formation of water vapor during processing which can give rise to several problems.[14,15] Recently, the hybridization with other reinforcing materials for improved the disadvantages of natural fiber composites is one of the interesting issue. The concept of hybrid systems for improved material performance is well known in engineering design. The behavior of hybrid composites is a weighed sum of the individual component in which there is a balance between the inherent advantages and disadvantages. The selection of the components is determined by the purpose of hybridization and requirements imposed on the material design. Hybrid green composites can be designed by the combination of synthetic fiber and natural fiber in a matrix. The effect of hybridization of glass fiber on mechanical properties in thermoset biocomposites and thermoplastic biocomposites has been discussed in detail by many researchers. Hybridization of natural fiber with glass fiber provides a method to improve the mechanical properties of green composite. Furthermore, a number of studies also report that the addition of glass fiber improved environmental durability of natural fiber composites.[16–26]

For the processing issue, the major processes that used in manufacturing of short fiber-reinforced polymer composites are extrusion compounding and injection molding because of the advantages in mass production. However, the extrusion compounding has a practical processing limit on the fiber attrition issue, which decreased the reinforcing efficiency of the fibers. Furthermore, for most of natural fiber, the primary problems in extrusion compounding of natural fiber with polymer matrix are the dosage and the homogeneous distribution of the fibers. Because of the low fiber density, the fibers are hard to pour into the compounding barrel. The solution to the dosing problem can be achieved through the using of long fiber thermoplastic granulation technology. In the recent years, there has been a rapid growth in the development of long fiber reinforced thermoplastic composites. Long fiber thermoplastics (LFT) have found general acceptance as structural materials and increased penetration of the automotive market. Long fiber-reinforced thermoplastic have excellent mechanical properties and stiffness-to-weight ratio. The largest segment of LFT composites is LFT polypropylene composites, which offered performance intermediate between short fiber-reinforced polymer and glass-mat thermoplastic (GMT) composites. Pultrusion is often used for producing long fiber thermoplastic pellets (LFT), which are

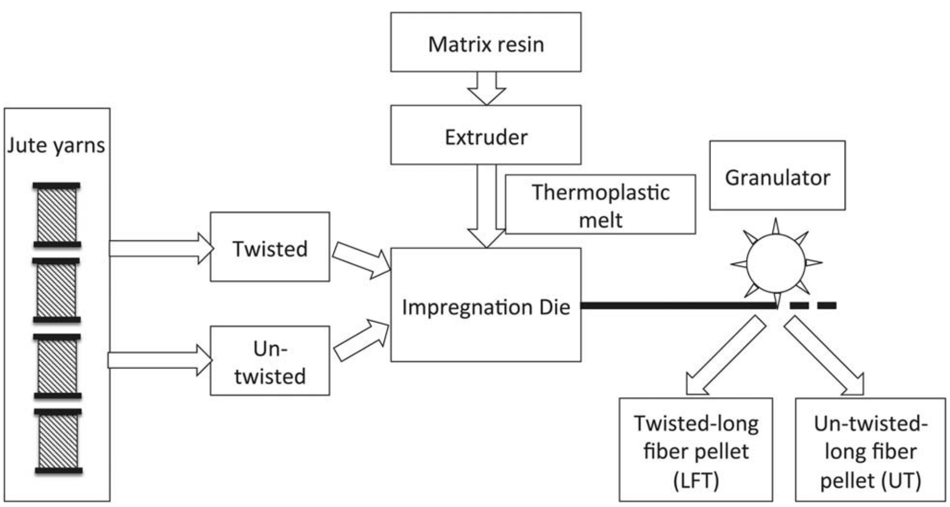

Figure 1. Schematic illustration represents the long fiber pultrusion process of twisted and un-twisted long fiber JF/PP pellet.

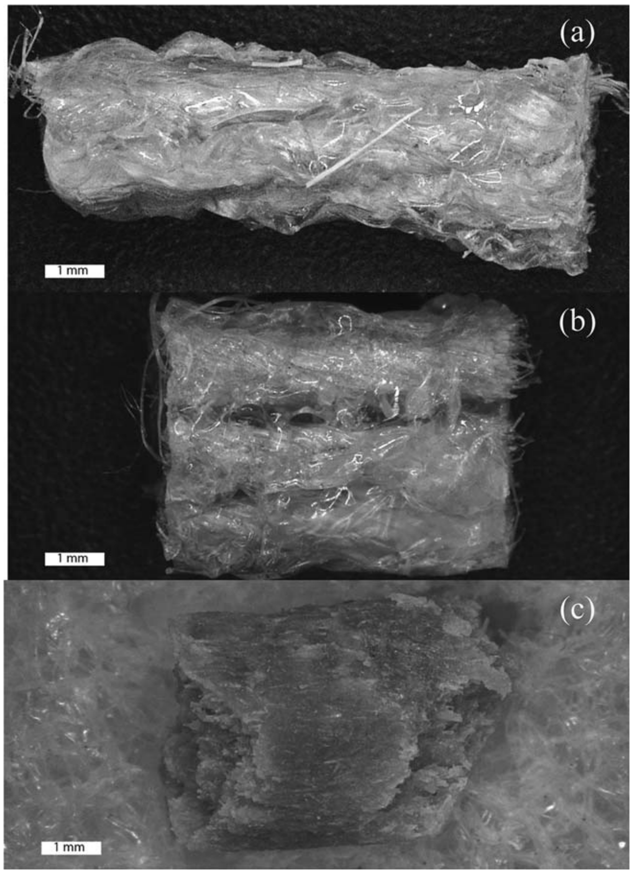

Figure 2. Characteristic of JF/PP pellets; (a) LFT-pellet, (b) UT-pellet, and (c) RP-pellet.

then used for producing relatively long fiber-reinforced polymer composites using conventional injection molding and compression molding. The precompounded LFT pellet can be supplied in highly loaded up to 70% fiber and can be diluted like a masterbatch to customize loading levels. The composites made with long glass fiber pellet in an injection molding exhibit the high strength and high stiffness values when compared with conventional short fiber-reinforced polymer composites.[27–32] Recently, many research works have been developed the fabrication of long natural fiber-reinforced thermoplastic through LFT technology. By the LFT technology, natural fiber-reinforced thermoplastic pellets with very high fiber concentration can be obtained. Furthermore, the reduction in thermal degradation of natural fiber during compounding was observed when compared with the conventional extrusion compounding because of the lower applied shear force. This LFT technology is a significant driving force for the using of natural fiber composite in automotive applications. Unlike synthetic fibers, most of natural fibers using in LFT technology are supplied in the form of spun yarns because of the requirement of continuous feeding of long fiber during pultrusion process. The advantages of using spun yarn to produce LFT natural fiber pellet are high fiber loading content and low variation of fiber content when compared with conventional compounding processes. To obtain the highest loading content, a number of natural fiber yarns are twisted together and passed through the impregnation die to produce long rods, which can be cut to obtain the pellets.[33–36]

In this study, in order to improve the distribution of jute fiber, the twisted and un-twisted of four jute yarns in long fiber jute fiber pellets were prepared by pultrusion technology. In addition, the re-compounded pellets of jute fiber pellet by extrusion compounding were also prepared to compare the effect of size of jute fibers. The effect of twisted and un-twisted jute yarn during LFT pellet preparation and re-compounding on mechanical properties of jute fiber/polypropylene composites was evaluated. In addition, the three different jute fiber pellets were dry blended with LFT glass fiber pellet to prepare hybrid composites. The mechanical properties enhancement efficiency of glass fiber hybridization with the using of different jute fiber pellet was determined.

EXPERIMENTAL

Materials and Specimen Preparation

In this study, jute fiber and glass fiber are selected as the reinforcement for polypropylene. The available properties and prices of reinforcements and matrix are listed in Table I. It is important to note that the prices, which are included in Table I, are adopted from several sources and thus may not represent the present state. In general, the commercial grade of jute yarn is produced by spinning process from short jute fiber with different twist factor for several applications. In the long fiber pellet making process of natural fiber, the common grade of jute yarn is selected to evaluate the effect of twisting process during pellet preparation. The twisted jute yarn (LFT-JF/PP) and un-twisted jute yarn (UT-JF/PP) pellets of jute fiber/polypropylene with 40 wt % jute fiber (supplied by Calp Co. Ltd.) were produced by the long fiber pultrusion process as schematically represented in Figure 1. For the making of LFT-JF/PP pellet, four jute yarns were twisted together and passed through the impregnation die. On the other hand, four jute yarns were separately passed through the impregnation die for the making of UT-JF/PP pellet. In order to keep the weight fraction of jute fiber at the same content for both jute long fiber pellets, the length of LFT- and UT-pellets were 8 and 4 mm, respectively. In addition, in order to compare composites fabricated from long fiber pellet

Table II. Specimen Designation and Composition of Composites

Code	Glass fiber (wt %)	Jute fiber (wt %)	Polypropylene (wt %)
PP	0	0	100
J10	0	10	90
J20	0	20	80
J30	0	30	70
J40	0	40	60
G10J0	10	0	90
G10J10	10	10	80
G10J20	10	20	70
G10J30	10	30	60

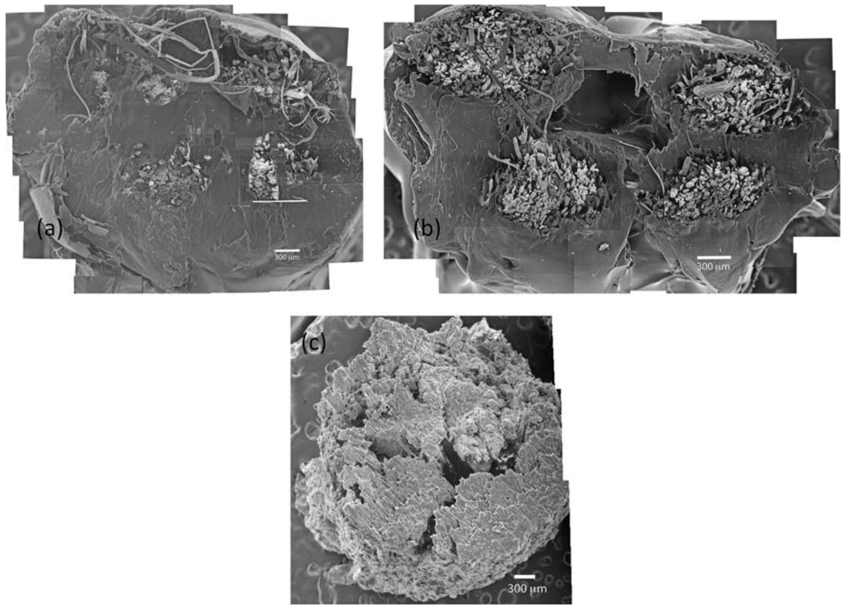

Figure 3. SEM micrograph of cross section of JF/PP pellets; (a) LFT-pellet, (b) UT-pellet, and (c) RP-pellet.

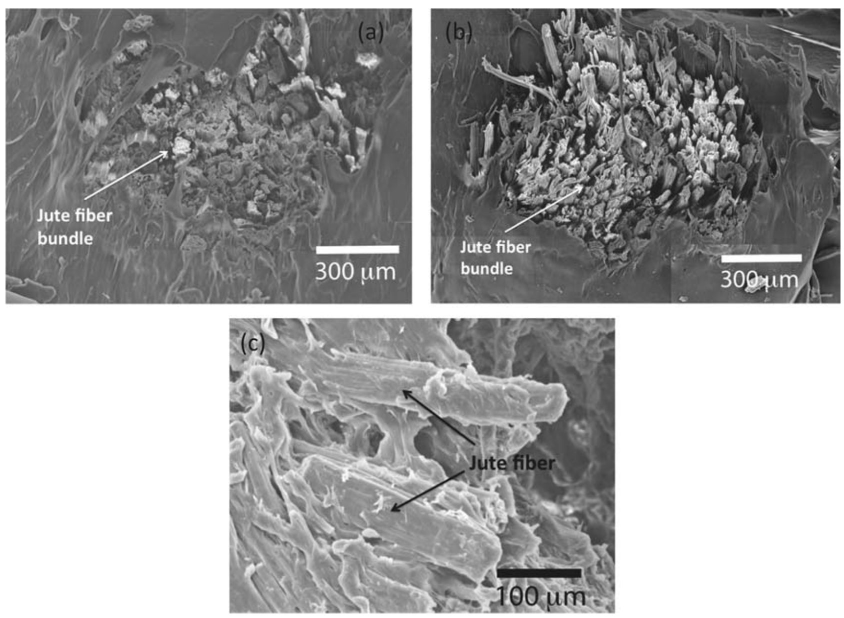

Figure 4. High magnification of SEM micrograph of cross section of JF/PP pellets; (a) LFT-pellet, (b) UT-pellet, and (c) RP-pellet.

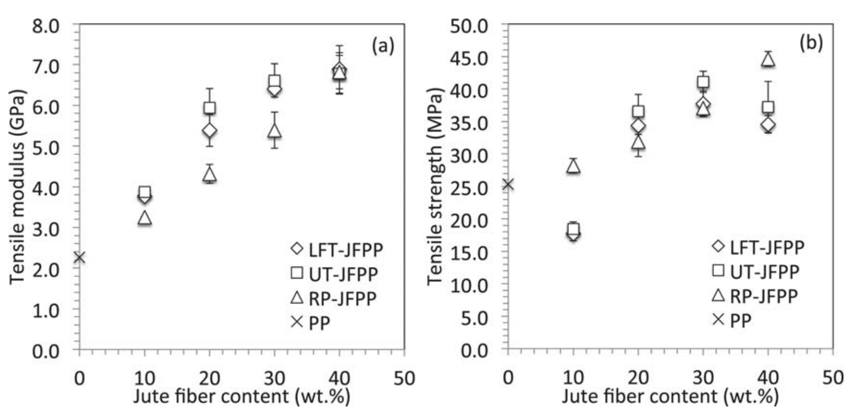

Figure 5. Tensile properties of JF/PP composites as a function of jute fiber content: (a) tensile modulus, (b) tensile strength.

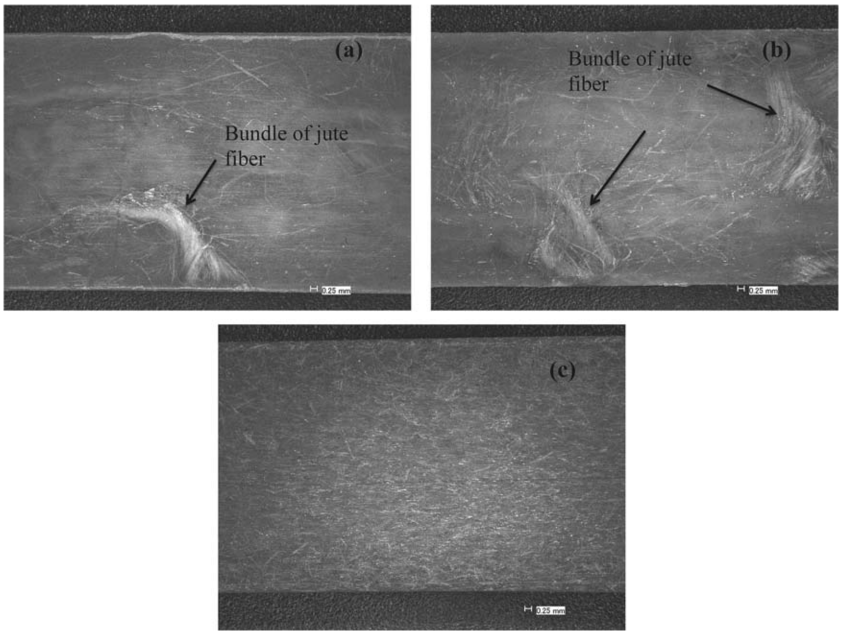

Figure 6. Micrograph of the middle part of 10 wt % JF/PP composites; (a) LFT-JF/PP, (b) UT-JF/PP, and (c) RP-JF/PP.

with short fiber pellet, the LFT-JF/PP pellets were re-compounded by using twin-screw extruder (JSW TEX30HSS) at barrel temperature 200°C and cut to the length of 4 mm to obtain the re-compounded pellets (RP-JF/PP pellet). The characteristic of three different JF/PP pellet were presented in Figure 2.

Besides jute/PP pellets, additionally, long fiber pellet of glass fiber/polypropylene (LFT-GF/PP) with 60 wt % glass fibers was also produced by long fiber pultrusion process (Calp Co. Ltd) to mold hybrid composites. The 2 wt % of maleic anhydride grafted polypropylene (MAPP) was added into both JF/PP and GF/PP pellet during pellet making process to improve the interfacial bonding between fiber and polypropylene matrix. The pellets were dry blended with polypropylene to obtain the desired composition for both monotonic and hybrid composites as shown in Table II. The dumbbell shape specimens were fabricated by injection molding machine (POYEUN 50 tons). The barrel temperatures were set at 200°C while injection and holding pressure were 85 and 70 MPa, respectively.

Testing

Tensile tests (ASTM D638) were performed with an Instron universal testing machine (Instron 4206 model) at a constant crosshead speed 1 mmmin^{-1}. The strain was measured by using

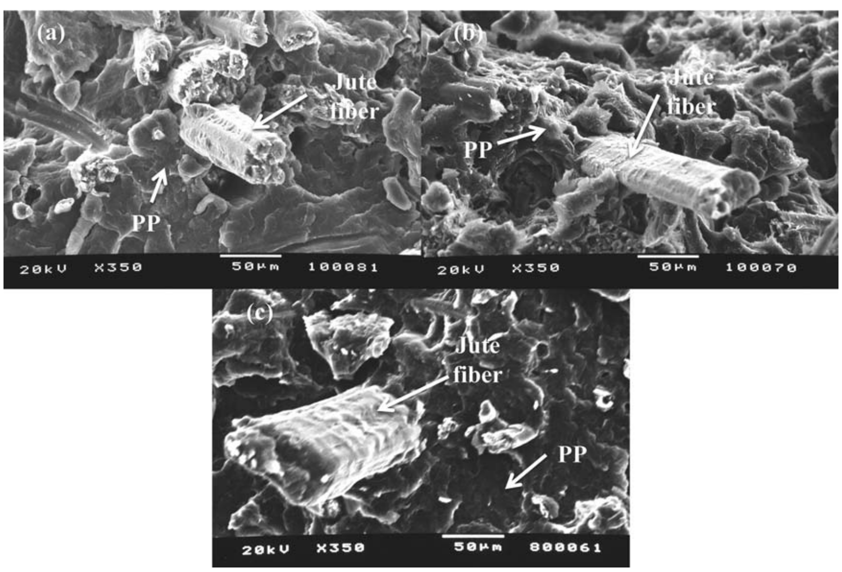

Figure 7. SEM micrograph of tensile fracture surface of JF/PP composites at x350 magnification; (a) LFT-JF/PP, (b) UT-JF/PP, and (c) RP-JF/PP.

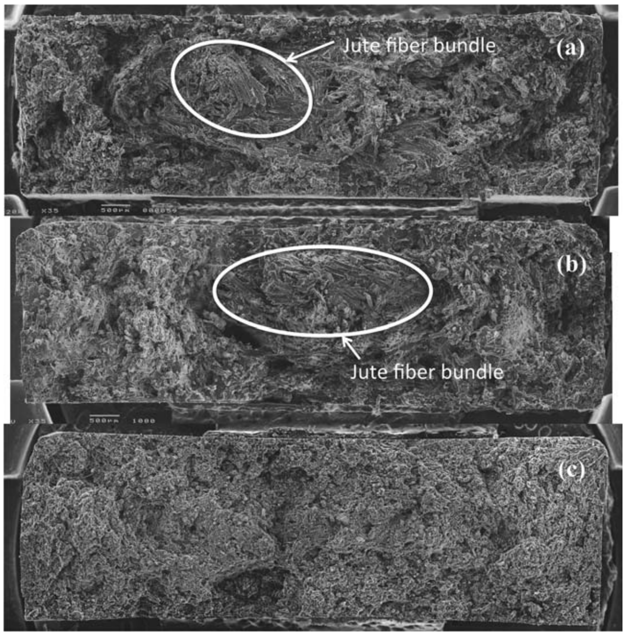

Figure 8. SEM micrograph of tensile fracture surface of 40 wt % JF/PP composites; (a) LFT-JF/PP, (b) UT-JF/PP, and (c) RP-JF/PP.

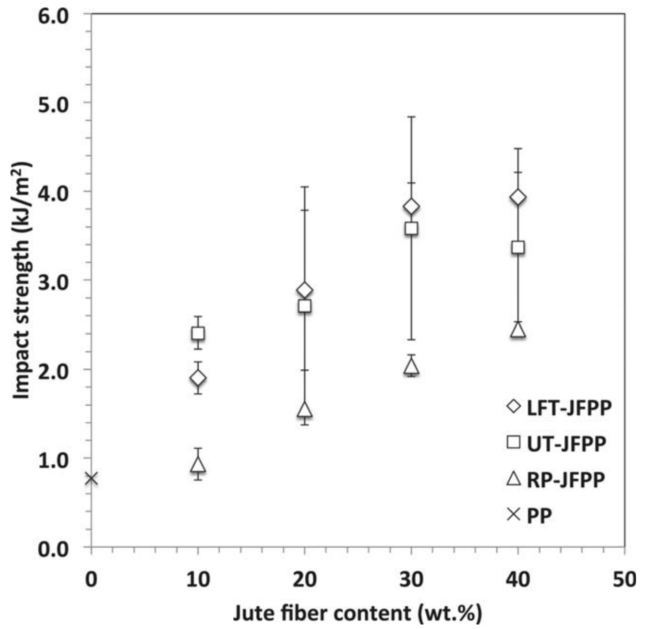

Figure 10. Notched Izod impact strength of JF/PP composites as the function of jute fiber content.

strain gauge extensometer. Three-point bending tests (ASTM D790) were also conducted with an Instron universal testing machine (Instron 4206 model). The testing speed was 1 mmmin^{-1} with span length 48 mm. Notched Izod impact tests were performed on the Digital Impact tester (Toyoseki) with 5.5 J pendulums in accordance with ASTM D256. The V-notch shape with 2 mm depth was prepared. At least five specimens were repeated for all tests.

Scanning Electron Microscopy Observation

Scanning electron microscopy (JEOL JSM 5200) was conducted on the fracture surface to examine the failure surface. The fracture ends of tensile-tested specimens were mounted on aluminum holders and gold sputtered for 6 min prior the observation to avoid electrical charging during observation.

Measurement of Fiber Length and Fiber Orientation

The $20 \times 10 \times 3$ mm piece was cut from the center of each tensile dumbbell. The glass fiber was subsequently separated from the matrix and jute fiber by burning off the resin using muffle furnace at 600°C for 6 h in order to completely eliminate both jute fiber and polypropylene matrix. The remained glass fiber were dispersed on glass slide and analyzed by using image analysis software. The weight average fiber length were defined by the following eq. (1):[1]

$$L_W = \sum N_i L_i^2 \Big/ \sum N_i L_i \tag{1}$$

where N_i is the number of fibers of length L_i.

Fiber orientation can be measured using an image analyzer system. The direct measurement of the elliptical parameters of each fiber allows the fiber orientation distribution to be measured. A 5 mm in length section was cut from the center of each tensile dumbbell. The samples were subsequently mounted in epoxy, polished, and photographed under microscope. The fiber orientation efficiency factor (f_o) can be determined by using the following eq. (2):[37]

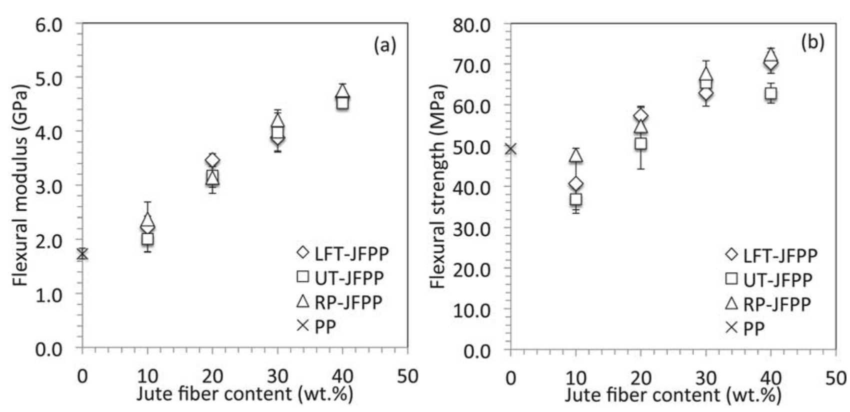

Figure 9. Flexural properties of JF/PP composites as a function of jute fiber content: (a) flexural modulus, (b) flexural strength.

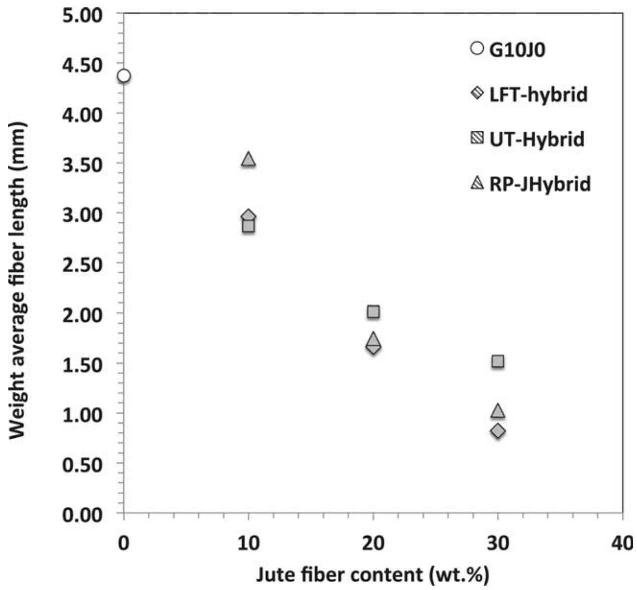

Figure 11. Weight average fiber length of glass fiber of GF/JF/PP hybrid composites as the function of jute fiber content.

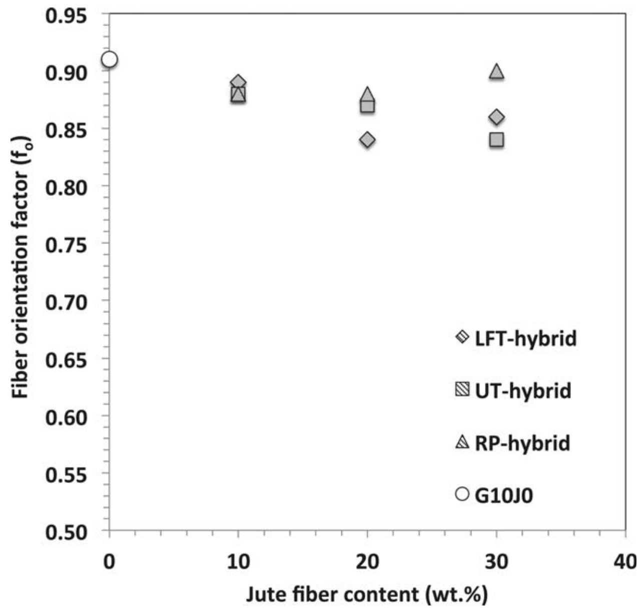

Figure 12. Fiber orientation efficiency of glass fiber of GF/JF/PP hybrid composites as the function of jute fiber content.

$$f_o = \sum a_n cos^4 \theta_n \tag{2}$$

Where a_n was the proportion of fibers making an angle $\theta_n$with respect to the flow direction.

RESULTS AND DISCUSSION

Characteristic of Jute Fiber/Polypropylene Pellet

The SEM micrographs of three different JF/PP pellets are presented in Figures 3 and 4. The surfaces of jute yarns are covered by PP matrix and showed good interfacial bonding. This is due to the effect of 2 wt % MAPP that was added during pellet making process. However, it can be seen that the impregnation between PP matrix and single fiber of jute fiber inside the yarn is poor for both LFT and UT long fiber pellet [Figure 4(a,b)]. On the other hand, the RP pellet shows better adhesion between single jute fiber and PP matrix as presented in Figure 4c. The extrusion compounding process significantly influences the shortening of jute fibers in the RP pellets through the shearing effect of the extruder screws.

Mechanical Properties of Jute Fiber/Polypropylene Composites

The tensile moduli of three different JF/PP composites are presented in Figure 5a. The stiffness of LFT-JF/PP and UT-JF/PP composites show similar value and increased with increasing of jute fiber content. There is no significant difference in tensile modulus between the using of twisted and/or un-twisted long fiber pellet. Tensile modulus of RP-JF/PP composites is lower than both LFT and UT composites because of the shorter fiber length of jute fiber in RP-JF/PP composites. Tensile strength of all three different JF/PP composites increases with jute fiber content with the exception of 10 wt % for LFT-JF/PP and UT-JF/PP composites as presented in Figure 5b. At 10 wt % jute fibers content, tensile strengths of LFT-JF/PP and UT-JF/PP are lower than the neat polypropylene matrix. The bundles of jute fiber are clearly found in LFT-JF/PP and UT-JF/PP composites as shown in Figure 6. These poor distributions of jute fiber bundle at low fiber content result as the high stress concentration and crack initiation site when stress applied to composites.

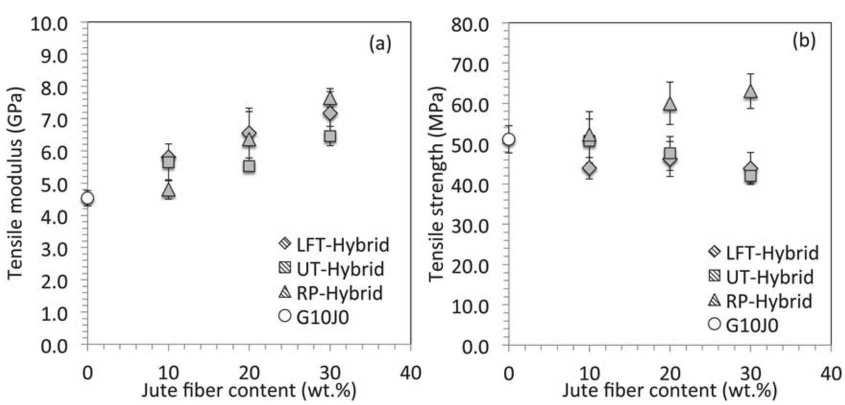

Figure 13. Tensile properties of GF/JF/PP hybrid composites as the function of jute fiber content: (a) tensile modulus, (b) tensile strength.

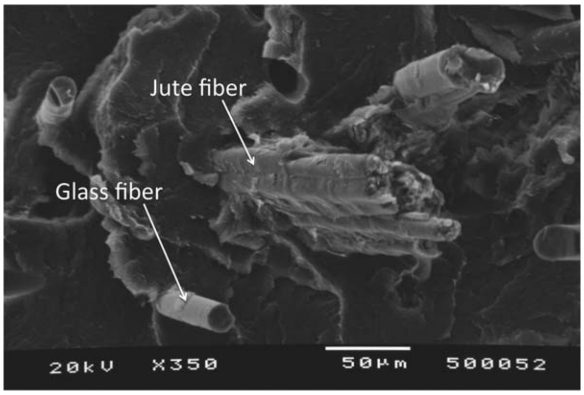

Figure 14. SEM micrograph of tensile fracture surface of GF/JF/PP hybrid composites at x500 magnification.

Tensile strength of LFT-JF/PP and UT-JF/PP increase with jute fiber content up to 30 wt %. Figures 7 and 8 represent the SEM micrographs of fracture surfaces of JF/PP composites after tensile test. The good interface between jute fiber and PP matrix results in effective stress transfer from matrix to fibers and exhibited the good reinforcing efficiency. Further increasing of jute fiber content decreases the tensile strength of LFT-JF/PP and UT-JF/PP composites. According to SEM observations in Figure 8, jute fibers of LFT-JF/PP and UT-JF/PP are aggregated in the bundle form at the core region and oriented in transverse direction. Moreover, the poor impregnation with matrix resin inside jute fiber bundle [Figure 4(a,b)] is expected to be the crack initiation site. These are the main factors incorporating with the poor fiber orientation which contributing to the low tensile strength of LFT-JF/PP and UT-JF/PP composites at 40 wt % jute fibers content. However, the tensile strength of jute

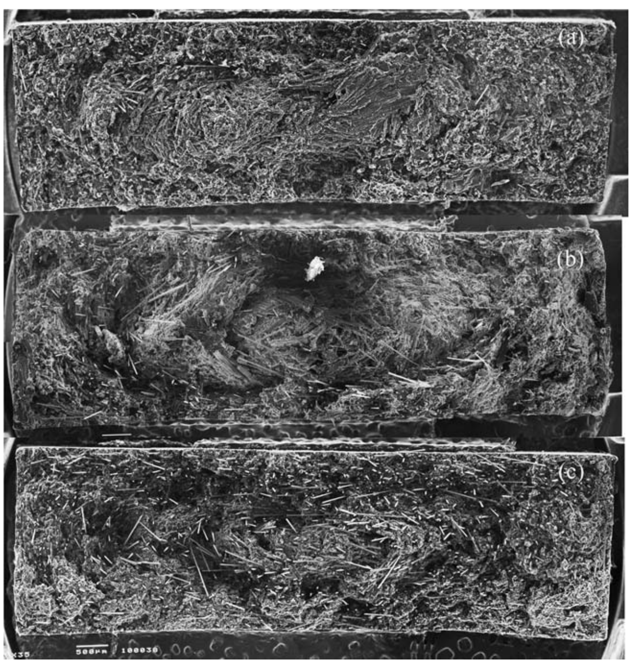

Figure 15. SEM micrograph of tensile fracture surface of 10 wt % glass fiber and 30 wt % jute fiber hybrid composites; (a) LFT-Hybrid, (b) UT-Hybrid, and (c) RP-Hybrid.

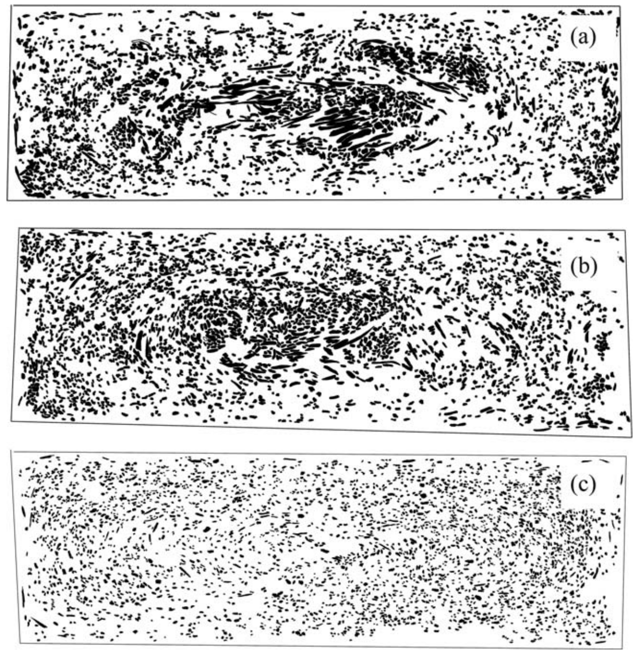

Figure 16. The marked photograph of jute fiber of hybrid composite shows different distribution of jute fibers; (a) LFT-Hybrid, (b) UT-Hybrid, and (c) RP-Hybrid.

fiber RP-JF/PP composite increased even at high fiber loading content. This indicates that the fiber distribution and fiber orientation play critical roles in determining the mechanical properties of JF/PP composites fabricated by injection molding.

Flexural properties of JF/PP composites as a function of jute fiber content are presented in Figures 9(a,b). The flexural moduli of all JF/PP composites show similar value and increase with the increase in jute fiber content. Unlike tensile property, there is no significant difference in flexural modulus of JF/PP composites between the using of different precompounded pellets. The results in Figure 9b indicate that flexural strength of all three different JF/PP composites increase with jute fiber content with the exception at 10 wt % fiber content for LFT-JF/PP and UT-JF/PP composites. This is due to the poor distribution of jute fiber as discussed previously.

The notched Izod impact strength of JF/PP composite as a function of jute fiber content is presented in Figure 10. It is clear that LFT- and UT-JF/PP composites perform significantly better impact property than the RP-JF/PP composites. This is because fiber length has a strong effect on impact strength of short fiber-reinforced composites. However, the differences of impact strength between LFT- and UT-JF/PP composites are insignificant. Furthermore, the large deviation from average value is observed for both LFT-JF/PP and UT-JF/PP composites. This is caused by the poor distribution of jute fiber, which is unable to separate from the bundle form.

Mechanical Properties of Glass Fiber/Jute Fiber/Polypropylene Hybrid Composites

In this study, the 10 wt % jute fibers are substituted by 10 wt % glass fibers for the preparation of hybrid composites as listed in Table I. Generally, fiber length and fiber orientation are the

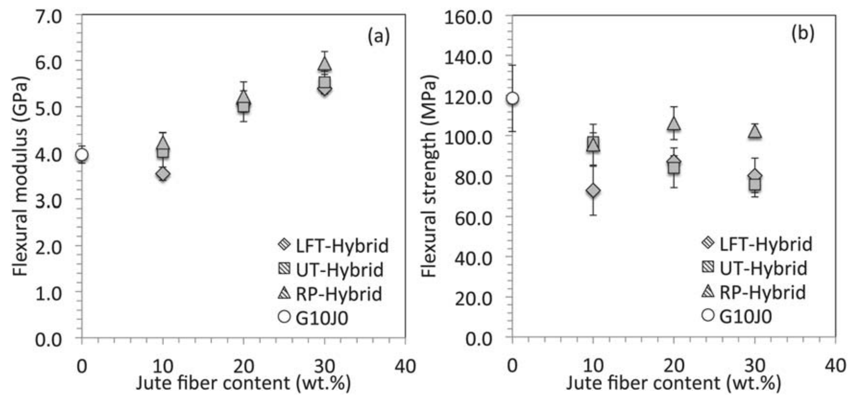

Figure 17. Flexural properties of GF/JF/PP hybrid composites as the function of jute fiber content: (a) flexural modulus, (b) flexural strength.

major factors that play critical roles in determining the performance of injection molded composites. In the case of hybrid composite of glass fiber and jute fiber, the stronger glass fiber is considered to be the main component that played the major role on mechanical properties of hybrid composite. The effects of the using of different JF/PP pellets on the characteristics of glass fibers such as the retained fiber length and fiber orientation of hybrid composite are discussed. Figure 11 shows the relationship between weight average fiber length of glass fiber and jute fiber content of three different hybrid composites. The average fiber length of glass fiber decreases with the increasing of jute fiber content for all hybrid composites. This indicates that interaction between glass fiber and jute fiber resulted in higher possibility to damage of the brittle glass fibers, while the effect of different JF/PP pellets on the breakage of glass fibers is insignificant. It seems that the glass fiber length might be affect by the volume not the length of jute fiber during the injection molding process.

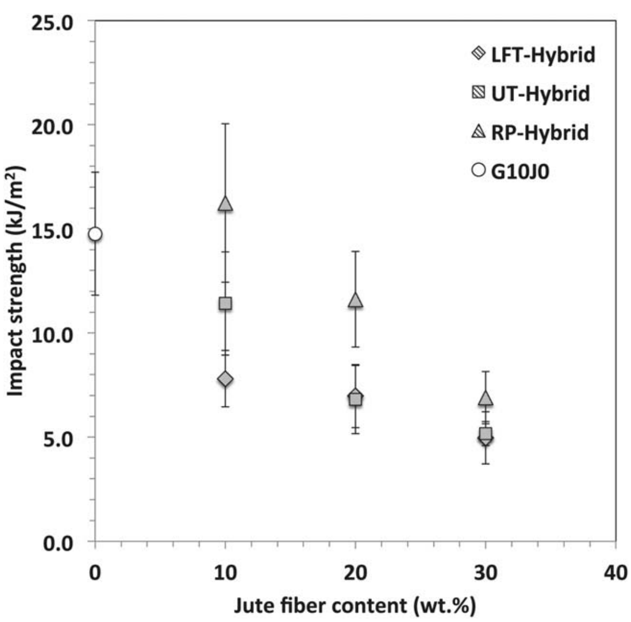

Figure 18. Notched impact strength of GF/JF/PP hybrid composites as the function of jute fiber content.

The plot of fiber orientation factor of glass fiber of several hybrid composites calculated from eq. (2) as a function of jute fiber content is presented in Figure 12. The orientation factor of 10 wt % monotonic glass fibers is 0.91. The bundles of jute yarns of long fiber pellets (LFT-JF and UT-JF) affect the orientation of glass fiber during injection molding which reduce the orientation factor of glass fibers. The effect of jute bundle on the orientation of glass fiber is more pronounce especially at high jute fiber content.

Figure 13a shows the relationship between tensile modulus and jute fiber content of GF/JF/PP hybrid composites. The tensile modulus of 10 wt % glass fibers hybrid composites increases with increasing jute fiber content. Unlike JF/PP composites, the tensile modulus of hybrid composites shows the different trend. As discussed previously, tensile modulus is dependent on the aspect ratio of jute fiber in the case of JF/PP composites. However, for hybrid-reinforced fiber system, the characteristics of both reinforcing fibers directly affect the stiffness of composites. Although, compared with RP-JF/PP pellets, the using of higher aspect ratio of jute fiber in LFT and UT-JF/PP pellets results in higher tensile modulus of JF/PP composites, tensile modulus of hybrid composites is not affected by the using of different JF/PP pellets. The lower modulus due to the lower jute fiber aspect ratio of RP-JF/PP composite is compensated by the higher fiber orientation factor of glass fiber in the case of RP-hybrid composite. It is worth to note that tensile modulus of hybrid composite mainly depends on the fiber orientation efficiency of the stiffer glass fiber.

However, the addition of 10 wt % glass fibers significantly affects the tensile strength of hybrid composites as presented in Figure 13b. It is observed that the increasing of mechanical properties of hybrid composites depended on type of JF/PP pellets. As discussed previously, the fiber distribution and fiber orientation play critical roles in determining the mechanical properties of JF/PP composites fabricated by injection molding. The similar results also observed in the case of hybrid composite.

From the SEM micrograph in Figure 14, both glass fiber and jute fiber show good interfacial bonding with polypropylene matrix. However, tensile strength of LFT and UT-hybrid composites decrease with increase in jute fiber content. On the other hand,

Table III. Summary of Mechanical Properties of JF/PP and GF/JF/PP Hybrid Composites

		JF/PP				GF/JF/PP		
Properties	Code	LFT	UT	RP	Code	LFT	UT	RP
Tensile modulus (GPa)	PP	2.26 ± ±0.01	2.26± ± 0.01	2.26 ± 0.01	PP	2.26 ± 0.01	2.26 ± 0.01	2.26 ± 0.01
	J10	3.76 ± 0.39	3.87 ± 0.48	3.25 ± 0.23	G10J0	4.53 ± 0.24	4.53 ± 0.24	4.53 ± 0.24
	J20	5.38 ± 0.07	5.94 ± 0.41	4.32 ± 0.44	G10J10	5.80 ± 0.03	5.65 ± 0.57	4.66 ± 0.37
	J30	6.40 ± 0.59	6.61 ± 0.51	5.39 ± 0.41	G10J20	6.55 ± 0.77	5.53 ± 0.17	6.36 ± 0.86
	J40	6.88 ± 0.12	6.79 ± 0.30	6.82 ± 0.08	G10J30	7.17 ± 0.66	6.46 ± 0.30	7.65 ± 0.29
Tensile strength (MPa)	PP	25.31 ± 1.09	25.31 ± 1.09	25.31 ± 1.09	PP	25.31 ± 1.09	25.31 ± 1.09	25.31 ± 1.09
	J10	17.69 ± 1.35	18.45 ± 2.57	28.15 ± 2.32	G10J0	51.09 ± 3.41	51.09 ± 3.41	51.09 ± 3.41
	J20	34.34 ± 1.98	36.55 ± 1.62	31.90 ± 1.22	G10J10	43.92 ± 2.67	50.67 ± 5.43	52.26 ± 5.69
	J30	37.70±1.32	41.09±3.95	37.02±1.13	G10J20	46.20 ± 4.34	47.47 ± 4.21	60.02 ± 5.25
	J40	34.54±0.19	37.21±0.18	44.61±0.58	G10J30	43.85 ± 4.00	42.04 ± 1.80	63.02 ± 4.31
Flexural modulus (GPa)	PP	1.74±0.10	1.74±0.10	1.74±0.10	PP	1.74 ± 0.10	1.74 ± 0.10	1.74 ± 0.10
	J10	2.22±0.46	2.01±0.24	2.38±0.05	G10J0	3.96 ± 0.19	3.96 ± 0.19	3.96 ± 0.19
	J20	3.46±0.12	3.17±0.21	3.14±0.29	G10J10	3.55 ± 0.14	4.02 ± 0.41	4.22 ± 0.22
	J30	3.88±0.25	3.97±0.36	4.20±0.19	G10J20	5.06 ± 0.18	5.01 ± 0.33	5.23 ± 0.31
	J40	4.63±0.07	4.52±0.01	4.75±0.12	G10J30	5.39 ± 0.12	5.53 ± 0.24	5.95 ± 0.25
Flexural strength (MPa)	PP	49.25±0.45	49.25±0.45	49.25±0.45	PP	49.25 ± 0.45	49.25 ± 0.45	49.25 ± 0.45
	J10	40.61±7.27	36.76±2.60	47.69±1.64	G10J0	118.64 ± 16.54	118.64 ± 16.54	118.64 ± 16.54
	J20	57.31±2.30	50.53±6.31	54.83±4.48	G10J10	72.75 ± 12.10	96.89 ± 4.50	95.55 ± 10.19
	J30	62.95 ± 3.29	65.39 ± 0.47	67.69 ± 3.10	G10J20	87.17 ± 2.94	84.04 ± 9.94	106.24 ± 8.19
	J40	70.36 ± 2.61	62.84 ± 2.46	72.45 ± 1.47	G10J30	80.23 ± 8.55	75.72 ± 6.21	102.48 ± 3.35
Impact strength (kJm^{-2})	PP	0.78 ± 0.18	0.78 ± 0.18	0.78 ± 0.18	PP	0.78 ± 0.18	0.78 ± 0.18	0.78 ± 0.18
	J10	1.90 ± 0.90	2.41 ± 1.34	0.93 ± 0.01	G10J0	14.76 ± 2.95	14.76 ± 2.95	14.76 ± 2.95
	J20	2.89 ± 0.26	2.71 ± 1.25	1.55 ± 0.12	G10J10	7.81 ± 1.35	11.42 ± 2.48	16.25 ± 3.81
	J30	3.83 ± 0.55	3.59 ± 0.84	2.04 ± 0.01	G10J20	6.97 ± 1.52	6.81 ± 1.64	11.62 ± 2.30
	J40	3.94 ± 0.38	3.37 ± 0.13	2.45 ± 0.12	G10J30	4.97 ± 1.25	5.17 ± 0.58	6.90 ± 1.25

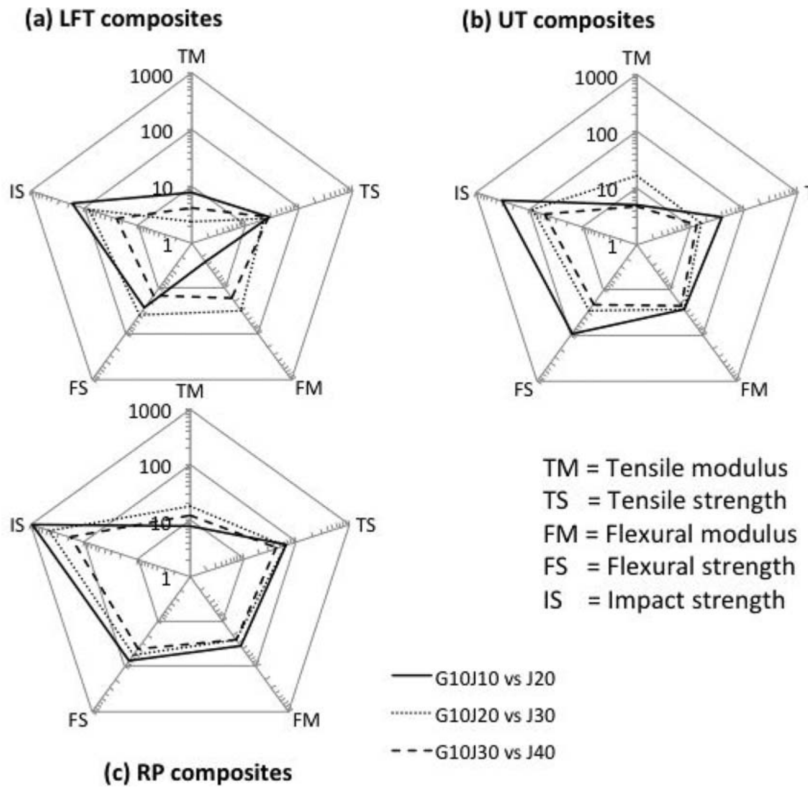

Figure 19. Percentage differentials of mechanical properties in comparison between monotonic JF/PP and 10 wt % glass fiber hybrids GF/JF/PP at same total fiber content.

the RP hybrid composite shows positive hybridization effect. This is due to the effect of different shape and size of jute fiber in JF/PP pellet, which affect the fiber length and fiber orientation of glass fiber incorporation with the degree of fiber distribution of jute fiber in hybrid composites. The effects of different JF/PP pellet on fiber length and orientation of glass fiber have been described in previous section. The shorter retained length and poorer orientation of glass fibers directly affect the tensile strength of LFT and UT-hybrid composite especially at high jute fiber content. In addition, as observed in Figure 15, the jute fibers of LFT and UT-hybrid composites aggregate in the bundle form at the core region and show transverse orientation to the flow direction. Not only the poor orientation of jute fiber, but the fiber aggregation of jute fiber also leads to the reduction of mechanical properties of hybrid composites. The photographs of polished surface of 30 wt % jute fiber hybrid composites are taken and the marking of jute fiber cross-section area are observed in order to evaluate the distribution level of jute fiber as presented in Figure 16. It can be seen that the bundle of jute fiber observed in LFT-hybrid (Figure 16a) and UT-hybrid (Figure 16b) composite are unable to separate into single fiber during molding and show poor fiber distribution when compared with RP-hybrid composite (Figure 16c). These poor fiber distributions directly affect the orientation of glass fiber, which lead to the reduction in tensile strength of hybrid composites when the content of jute fiber increased.

Figure 17a shows the relationship between flexural modulus and jute fiber content of GF/JF/PP hybrid composites. The flexural modulus of 10 wt % glass fibers hybrid composites increases with increasing jute fiber content and is not affected by the types of JF/PP pellets. However, the increase in jute fiber contents significantly reduces flexural strength and impact strength of hybrid composites for all type of JF/PP pellet as presented in Figure 17b and Figure 18, respectively. This is due to the drastically decreased of retained glass fiber length in hybrid composites with the increase in jute fiber content. Generally, the length of retained glass fiber is the major parameter that affected the mechanical properties of short fiber-reinforced composites. However, from the results in this study, the effect of fiber length reduction is more pronounce on flexural strength and impact strength of hybrid composites than the tension load.

The mechanical properties of JF/PP composites and its hybrid with 10 wt % glass fibers are summarized in Table III. From the Table III, it can be observed that the hybridization of glass fiber in JF/PP composites shows different effect with different types of JF/PP pellets. In order to evaluate the effectiveness of mechanical enhancement by substitution of 10 wt % glass fibers with different JF/PP pellet, the percentage differential of mechanical properties between JF/PP and hybrid composites are calculated from the difference of mechanical properties between 10 wt % glass fiber hybrid composite comparing with JF/PP composite at the same fiber loading content, for example G10J10 versus J20. The percentage of mechanical properties improvement from the addition of 10 wt % glass fibers is presented in Figure 19 in order to clarify the effect from the types of JF/PP pellets. The improvement of tensile modulus from the incorporation of 10 wt % glass fiber ranges from 4 to 18% for all types of JF/PP pellets. On the other hand, the effect of hybridization of 10 wt % glass fibers is more pronounce on flexural modulus, which ranges from 16 to 30% improvement. The effectiveness of glass fiber hybridization is highest when combined with RP-JF/PP pellet composites for tensile strength (64%), flexural strength (74%), and impact strength (948%), respectively, when comparing at 20 wt % total fiber content. The reasons for these occurrences are the better fiber orientation of glass fiber and the better distribution of jute fiber of hybrid composites as previously discussed. This indicates that the characteristics of the higher strength glass fiber such as fiber orientation and fiber length are the major factor that controlled the mechanical properties of hybrid composites. The using of LFT technology for the production of long fiber pellet of natural fiber is a huge step for the development of high performance natural fiber-reinforced composites. However, the effect of fiber distribution must be considered in order to achieve the best reinforcing effect. Furthermore, in the case of hybridization with glass fiber, the retained length of glass fiber is the critical parameter that controlled the mechanical properties of composites.

CONCLUSIONS

This study reports the effect of size and shape of jute fiber on the mechanical properties of jute fiber and glass/jute fiber hybrid reinforced polypropylene composites prepared by injection molding. The results of this study can be concluded as the following

Mechanical properties of JF/PP composites are mainly depended on the fiber aspect ratio, fiber orientation, and the distribution of jute fibers. The using of longer fiber results in high stiffness and high impact strength. However, the longer fiber bundle consequently affects the distribution and orientation efficiency of jute fiber, which results in the reduction of tensile strength.

The incorporation of 10 wt % glass fibers is found to improve mechanical properties of jute fiber-reinforced polypropylene composites. Although the mechanical properties of hybrid composites are affected by glass and jute fiber, the characteristics of the higher strength glass fiber such as fiber orientation and fiber length are the major factor that controlled the mechanical properties of hybrid composites. However, the increase in mechanical properties of hybrid composites was depended on type of JF/PP pellets. In addition with the poor orientation of jute fiber, the fiber aggregation also leads to the reduction in mechanical properties of hybrid composites.

All these results indicated that the injection molded glass fiber/ jute fiber /PP hybrid composites result in enhanced performance of natural fiber composites. In addition, by the LFT technology, natural fiber-reinforced thermoplastic pellets with very high fiber concentration can be obtained. This LFT technology is a significant driving force for the using of natural fiber composite in automotive applications. However, in order to maximize the effectiveness of glass fiber hybridization, the fiber distribution and fiber orientation of jute fiber might be seriously considered.

REFERENCES

1. Fu, S. Y.; Lauke, B.; Mai, Y. W. Science and engineering of short fiber reinforced polymer composites; CRC press: Boca Raton, Florida, **2009**; pp 1.
2. Joshi, S. V.; Drzal, L. T.; Mohanty, A. K.; Arora, S. *Compos. Part A: Appl. Sci. Manu.* **2004**, *35*, 371.
3. Pickering, K. L. Properties and performance of natural-fiber composites; CRC press: Boca Raton, Florida, **2008**; pp 3.
4. Koronis, G.; Silva, A.; Fontul, M. *Compos. Part B: Eng.* **2013**, *44*, 120.
5. Cheung, H. Y.; Ho, M. P.; Lau, K. T.; Cardona, F.; Hui, D. *Compos. Part B: Eng.* **2009**, *40*, 655.
6. Wang, J.; Qiang, S. S.; Liang, K. *J. Agri. Sci. Tech. B* **2013**, *3*, 493.
7. Goda, K.; Cao, Y. *J. Solid. Mech. Mater. Eng.* **2007**, *1*, 1073.
8. Ashori, A. *Bioresource Technol.* **2008**, *99*, 4661.
9. La Mantia, F. P.; Morreale, M. *Compos. Part A: Appl. Sci. Manu.* **2011**, *42*, 579.
10. Gassan, J.; Bledzki, A. K. *Compos. Part A: Appl. Sci. Manu.* **1997**, *28*, 1001.
11. Valadez-Gonzalez, A.; Cervantes-Uc, J. M.; Olayo, R.; Herrera-Franco, P. J. *Compos. Part B: Eng.* **1999**, *30*, 309.
12. Mahlberg, R.; Paajanen, L.; Nurmi, A.; Kivisto, A.; Koskela, K.; Rowell, R. M. *Eur. J. Wood. Wood. Prod.* **2001**, *59*, 319.
13. Yanjun, X.; Callum, A. S. H.; Zefang, X.; Holger, M.; Carsten, M. *Compos. Part A: Appl. Sci. Manu.* **2010**, *41*, 806.
14. Xue, Y.; Veazie, D. R.; Glinsey, C.; Horstemeyer, M. F.; Rowell, R. M. *Compos. Part B: Eng.* **2007**, *38*, 152.
15. Zabihzadeh, S. M. *BioResources* **2009**, *5*, 316.
16. Hardaker, K. M.; Richardson, M. O. W. *Polym. Plast. Tech. Eng.* **1980**, *15*, 169.
17. Ashby, M. F.; Brechet, Y. J. M. *Acta. Mater.* **2003**, *51*, 5801.
18. Fu, S. Y.; Lauke, B. *Compos. Part A: Appl. Sci. Manu.* **1998**, *29*, 575.
19. Arbelaiz, A.; FernaÇndez, B.; Cantero, G.; Llano-Ponte, R.; Valea, A.; Mondragon, I. *Compos. Part A: Appl. Sci. Manu.* **2005**, *36*, 1637.
20. Velmurugan, R.; Manikandan, V. *Compos. Part A: Appl. Sci. Manu.* **2007**, *38*, 2216.
21. Jarukumjorn, K.; Suppakarn, N. *Compos. Part B: Eng.* **2009**, *40*, 623.
22. Samal, S. K.; Mohanty, S.; Nayak, S. K. *J. Reinf. Plast. Compos.* **2009**, *28*, 2729.
23. Jawaid, M. H. P. S.; Abdul Khalil, H. P. S. *Carbohyd. Polym.* **2011**, *86*, 1.
24. Thwe, M. M.; Liao, K. *Compos. Sci. Tech.* **2003**, *63*, 375.
25. Pothan, L. A.; Thomas, S.; J. *Appl. Polym. Sci.* **2004**, *91*, 3856.
26. Panthapulakkal, S.; Sain, M. J. *Appl. Polym. Sci.* **2007**, *103*, 2432.
27. Czigany, T.; Karger-Kocsis, J. *Polym. Bull.* **1993**, *31*, 495.
28. Thomason, J. L. *Compos. Part A: Appl. Sci. Manu.* **2002**, *33*, 1641.

29. Thomason, J. L. *Compos. Part A: Appl. Sci. Manu.* **2005**, *36*, 995.
30. Kumar, K. S.; Ghosh, A. K.; Bhatnagar, N. *Polym. Compos.* **2007**, *28*, 259.
31. Fu, X.; He, B.; Chen, X. *J. Reinf. Plast. Compos.* **2010**, *29*, 936.
32. Wang, J.; Geng, C.; Luo, F.; Liu, Y.; Wang, K.; Fu, Q.; He, B. *Mater. Sci. Eng. A: Struct.* **2011**, *528*, 3169.
33. Arzondo, L. M.; Vazquez, A.; Carella, J. M.; Pastor, J. M. *Polym. Eng. Sci.* **2004**, *44*, 1766.
34. Arzondo, L. M.; Perez, C. J.; Carella, J. M. *Polym. Eng. Sci.* **2005**, *45*, 613.
35. Yang, Y.; Ota, T.; Morii, T.; Hamada, H. *J. Mater. Sci.* **2011**, *46*, 2678.
36. Jeyanthi, S.; Janci Rani, J. *J. Appl. Sci. Eng.* **2012**, *15*, 275.
37. Patcharaphun, S.; Mennig, G. *J. Met. Mater. Miner.* **2007**, *17*, 9.