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# Evaluation of quasi-isotropic plate and cylindrical shell fabricated with green composite sheets

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# Evaluation of quasi-isotropic plate and cylindrical shell fabricated with green composite sheets

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Conventional fiber reinforced plastics (FRPs) have some problems in the case of disposal. Their combustion disposal discharges the carbon dioxide in the air because resins of FRPs are made of fossil fuel. In the case of disposal into the ground, these FRPs remain semi-permanently without decomposing. Therefore, green composites are now developed and are studied as one of less the environmental burden materials. In this study, two kinds of continuous green composite sheets, which were composed of Kenaf fibers or Linen fibers as reinforcement and biodegradable poly butylene succinate (PBS) resin as a matrix, were fabricated with a pultrusion molding. Since the PBS resin is a thermoplastic resin, the PBS/KENAF or PBS/LINEN composite sheets can be treated as intermediate materials such as Carbon Fiber Reinforced Plastic prepregs. In order to apply the PBS/KENAF or PBS/LINEN composite sheets to structural components, quasi-isotropic plates and cylindrical shells were fabricated and evaluated.

**Keywords:** pultrusion molding; green composite sheet; shell; plate

## 1. Introduction

Fiber reinforced plastics (FRPs) have some problems in the case of disposal because resins of FRPs are made of fossil fuel. One of the problems is that carbon dioxide increases in the air owing to the combustion disposal. Another problem is that the FRPs remain without decomposing in the ground because of their semi-permanent durability. Therefore, a development of new composites made of natural fibers and biodegradable resins is expected. These new composites are called ‘green composites’. For example, various natural fibers such as pineapple fiber, flax fiber, bamboo fiber, and ramie fiber were adopted as reinforcement for green composites and evaluated their mechanical properties.[1–4] In order to improve the mechanical properties of green composites, water treatment,[5] and surface modified for jutes were examined.[6] In order to characterize green composites, the thermal barrier properties of bamboo reinforced composites [7] and the fatigue properties of jute reinforced composites [8] were measured.

On the other hand, unidirectional green composite materials, which were made of Kenaf fibers as a reinforcement and biodegradable poly butylene succinate (PBS) resin as a matrix, were fabricated with a pultrusion molding.[9] The heat-resistant tensile properties of this green composite were examined.[10]

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The aim of this study is to develop a fabrication method for green composites used woven fabric of 150 mm width as reinforcement by a pultrusion molding. These green composite sheets can be continuously fabricated and can be treated an intermediate material such as carbon fiber reinforced plastic (CFRP) prepregs. This continuous fabrication method is the first trial in the field of green composites as far as the authors know and a valuable method to apply the green composites to industrial goods. Concretely, these green composites were applied to fabricate quasi-isotropic plates and cylindrical shells and their mechanical properties were evaluated.

## 2. Green composite sheets

### *2.1. Fabrication method*

The 150 mm width of the plain woven fabric of Kenaf or Linen (Figure 1) was used as reinforcement. As a matrix, PBS pellets (PBS1050, showa denko Co., Ltd.) were used. They are one of thermoplastic resin (Figure 2). The properties of PBS1050 resin are listed in Table 1.

A schematic diagram of the pultrusion facilities is shown in Figure 3(a) and (b). Since PBS pellets are solid resin under the room temperature, an extrusion (KZW15TTW-45MG, Technovel Co., Ltd.) was used to melt and to inject the melted PBS resin into the cross head die having heaters (Figure 3(a)). In order to pull the woven fabric and to keep suitable position of the woven fabric during impregnation, a guide and a tensioner were installed between the fabric roll and the cross head die (Figure 3(b)). The outlines of molding process were described as follows:

(1) The feeding hopper of the extruder was filled with the PBS pellets. The PBS pellets were heated and melted in the extruder and the melted PBS resin was extruded into the cross-head die.
(2) The reinforcement fabric was drawn into the cross-head die by using the pulling machine and it was impregnated with the melted PBS resin inside the heated cross head die.
(3) The pulled out green composite sheet was cooled in the air between the cross-head die and the pulling machine. Then it was cut with optional length.

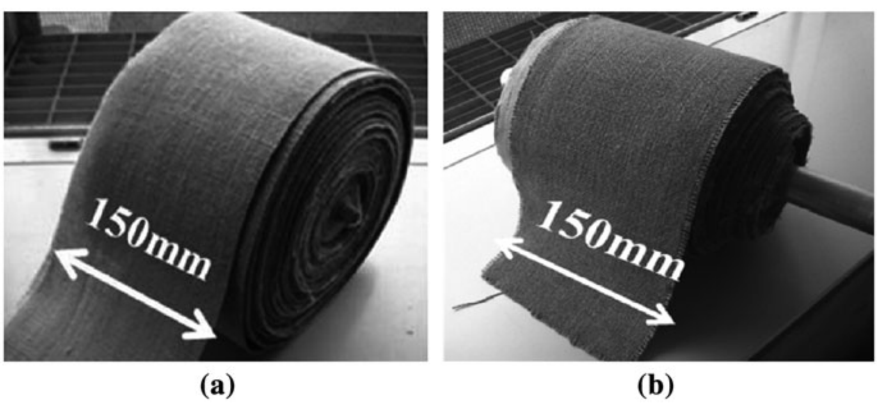


Figure 1. Fabrics: (a) Kenaf fabric, (b) Linen fabric.

Figure 2. PBS pellets.



Table 1. Grade of PBS1050 resin.

| Material | Company | Grade | Density [g/cm$^3$] | Young's modulus [GPa] | Flexural strength [MPa] | Melting point [°C] |
|---|---|---|---|---|---|---|
| PBS1050 | Showa Denko C.O. | ♯ 1050 | 1.26 | 0.8 | 34.3 | 115 |

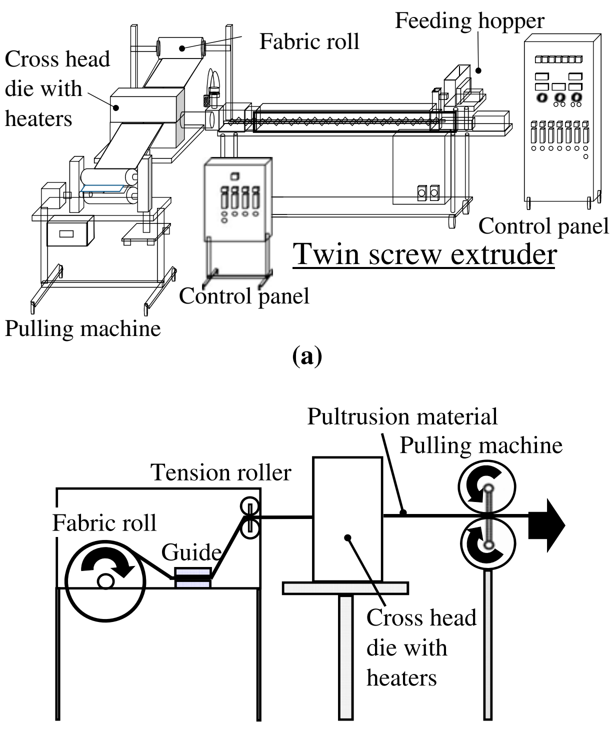


Figure 3. Schematic diagram of pultrusion method.

### 2.2. *Consideration of viscosity of resin*

Since the melted PBS resin had high viscosity, the fabric lines normal to the pulling direction (in the weft direction) became to be curved as shown in Figure 4, and the impregnation of the melted PBS resin to the reinforcement fabric is difficult. In order to decrease the viscosity of resin by changing the molding temperature, a trial test was carried out by using polypropylene (PP, NOVATEC BC06C) which was inexpensive and easy to change its viscosity by heating. From the test, the fabric lines of Kenaf were not curve and kept the straight fabric lines after the pultrusion at the temperature of over 230 °C and the PP's melting flow rate (MFR) was 62 g/10 min at that case. In the PBS resin system, the MFR of PBS 1050 showed the same value at the temperature of 190 °C (Figure 5). Since the Kenaf fabrics did not receive any damage at this temperature,[10] the green composite sheets of Kenaf and Linen fabrics with PBS 1050 resin could be obtained with pultrusion molding without the fabric lines curved and their photographs are shown in Figure 6(a) and (b). Hereafter, they are called PBS/KENAF and PBS/LINEN in this paper, respectively.

## 3. Green composite plates

### 3.1. *Orthotropic plates*

Since the PBS is the thermoplastic resin, the green composite sheet can be treated as an intermediate material. The green composite sheet (thickness of 1.3 mm, width of

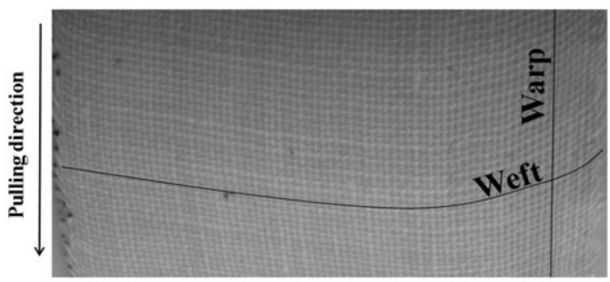


Figure 4. Movement of weft fibers in kenaf fabric.

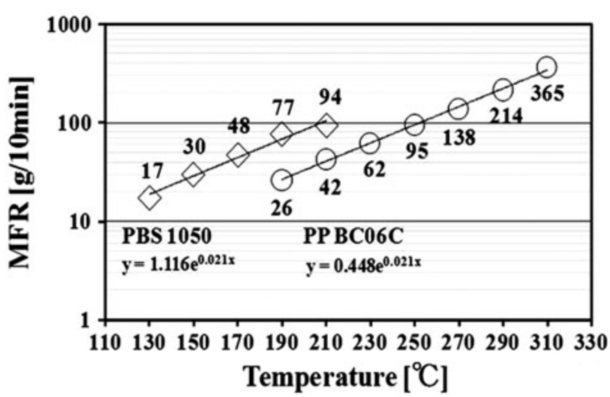


Figure 5. MFR of PBS1050 and PP BC06C resins.

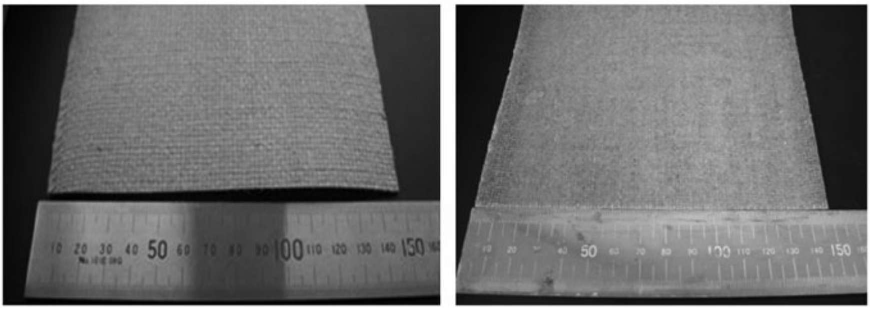


Figure 6. Pultrusion composites: (a) PBS/KENAF sheet, (b) PBS/LINEN sheet.



150 mm) was cut to a length of 280 mm. Then, four green composite sheets were stacked with the accordance of fiber directions, and they were inserted into the hot press apparatus with metallic dies under the temperature and the pressure of 150 °C and 1.5 MPa for 3 min. Then, it was cooled over 10 min under a compression of about 10 MPa. The four ply orthotropic plates of PBS/KENAF and the PBS/LINEN were cut to the size of 250 × 25 × 2 mm as the test specimens. The 2 mm thickness tabs were bonded to the both end of the specimens and the gauge length was 150 mm.

The tensile tests of the five specimens were carried out based on JIS K 7164. The test speed was 1 mm/min. The test results are shown in Table 2. The volume fraction of fiber of PBS/LINEN was 39% and that of PBS/KENAF was 33%. The tensile strength and the elastic modulus of PBS/LINEN were about 60 and 30% larger than those of PBS/KENAF, respectively. Figure 7 shows the representative stress/strain curves of PBS/KENAF and PBS/LINEN. These curves also indicated that the fracture strain of PBS/LINEN was 30% larger than that of PBS/KENAF.

Table 2. Tensile test results of PBS/KENAF and PBS/LINEN specimens.

| | Vf [%] | Specimens number | Tensile strength [MPa] | Failure strain [%] | Young's modulus [GPa] |
|---|---|---|---|---|---|
| PBS/KENAF | 33 | 1 | 49.2 | 2.58 | 3.53 |
| | | 2 | 48.7 | 2.71 | 3.40 |
| | | 3 | 47.6 | 2.88 | 3.25 |
| | | 4 | 46.7 | 3.75 | 2.88 |
| | | 5 | 43.0 | 2.61 | 3.20 |
| | | Ave. | 47.0 | 2.91 | 3.25 |
| | | (Standard deviation) | (2.461) | (0.486) | (0.245) |
| PBS/LINEN | 39 | 1 | 76.4 | 3.63 | 4.12 |
| | | 2 | 75.5 | 3.55 | 4.12 |
| | | 3 | 79.1 | 3.63 | 4.69 |
| | | 4 | 74.7 | 3.35 | 4.22 |
| | | 5 | 79.9 | 3.69 | 4.31 |
| | | Ave. | 77.1 | 3.57 | 4.29 |
| | | (Standard deviation) | (2.271) | (0.133) | (0.236) |

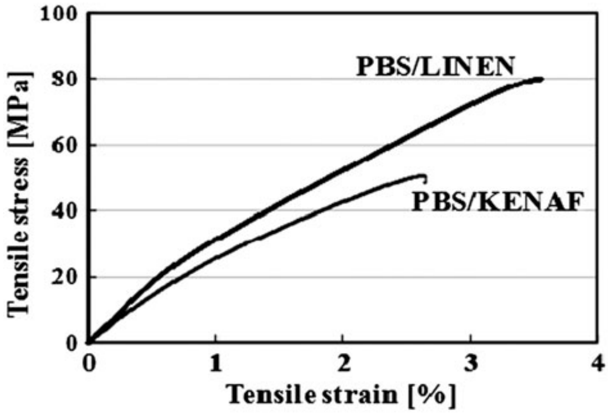


Figure 7. Stress–strain curves of PBS/KENAF and PBS/LINEN specimens.



### *3.2. Quasi-isotropic plate*

The quasi isotropic green composite plate was fabricated with the same process as the orthotropic plate. The green composites sheets were stacked as [0–90°/±45°]s for realizing the quasi-isotropy. After fabricating the quasi-isotropic plate, the test specimens were cut out with the angle of 0°, 45°, and 90° to the pulling direction. Figure 8 shows the cutting direction.

The tensile tests were carried out based on JIS K 7164, with a test speed of 1 mm/min. The test results are shown in Table 3. Since the tensile results of 0°, ±45° and 90° specimens were presented almost the same values, this green composite plate showed the isotropic properties.

## 4. Green composite cylindrical shell

### *4.1. Fabrication*

The cylindrical shell with green composite of PBS/ LINEN was fabricated by means of the tape winding method. The stacking sequence was [±45°/0–90°]s to fabricate the

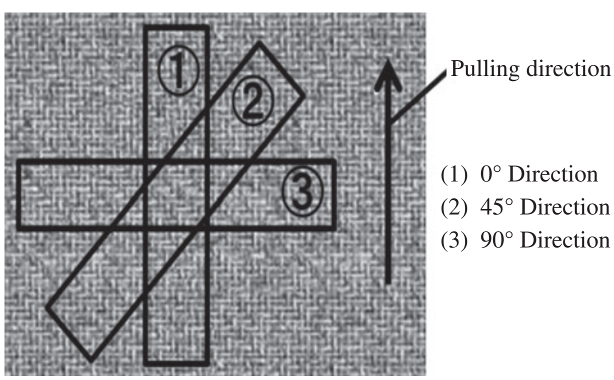


Figure 8. Quasi-isotropic PBS/LINEN.

Table 3. Tensile test results of quasi-isotropic PBS/LINEN specimens.

| Direction | Tensile strength [MPa] | Failure strain [%] | Young's modulus [GPa] |
|---|---|---|---|
| 0° | 53.5 | 3.65 | 2.19 |
| (Standard deviation) | (1.741) | (0.072) | (0.142) |
| 45° | 52.9 | 3.54 | 2.50 |
| (Standard deviation) | (1.034) | (0.233) | (0.087) |
| 90° | 52.7 | 3.85 | 2.17 |
| (Standard deviation) | (0.291) | (0.122) | (0.067) |

quasi-isotropic shell. Figure 9 shows the stacking sequence in the thickness direction of cylindrical sell. The outlines of molding process were described as follows:

(1) The innermost sheet of cylinder was wound helically to the mandrel under tension at the room temperature. Then, the sheets were fixed at both ends with a heat-resistant tape (Figure 10(a)).
(2) The 2nd and 3rd sheets cut from the green composite sheets were wound as the hoop sheets. In the 2nd and 3rd sheets, discontinuous places due to the width of green composite sheets were shifted along the circumferential direction (Figure 10(b)).
(3) The outermost sheet was wound helically as the same as innermost sheet fabrication.
(4) After a peel ply was wound over the outermost sheets, the laminated cylinder with the mandrel was placed under vacuum. The peel ply prevented the kink of

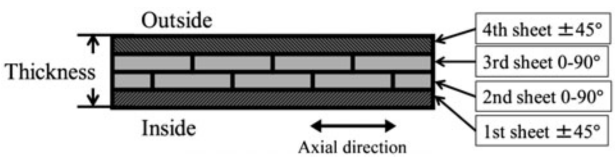


Figure 9. Stacking sequence of cylindrical shell.

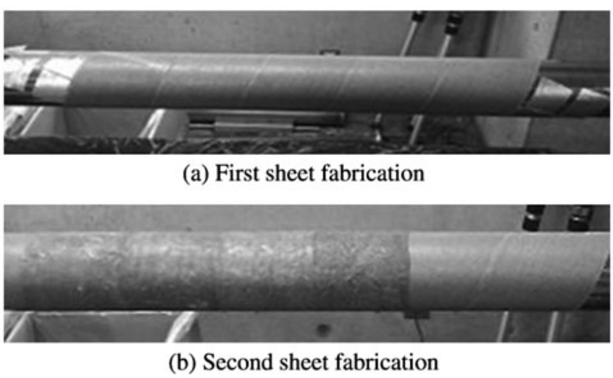


Figure 10. Fabrication of cylindrical shell.

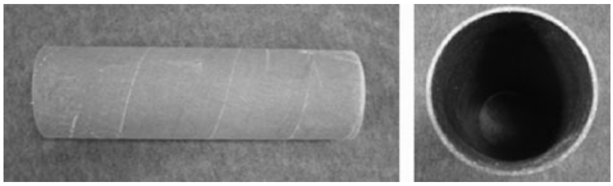

Figure 11. Cylindrical shell of PBS/LINEN.

fibers and it removed the extra resin. The resin was re-melted one more time with a furnace at 170 °C. As the final process, the laminated cylinder was cured by air cooling (Figure 11).



### 4.2. *Axial compression*

In order to evaluate the performance of structural members made of the green composites, the axial compression test was carried out as shown in Figure 12. Two strain gauges of 180° interval were pasted to the surface of a cylindrical shell. The shell dimensions of each specimen were measured as shown in Table 4. The thickness of each specimen was

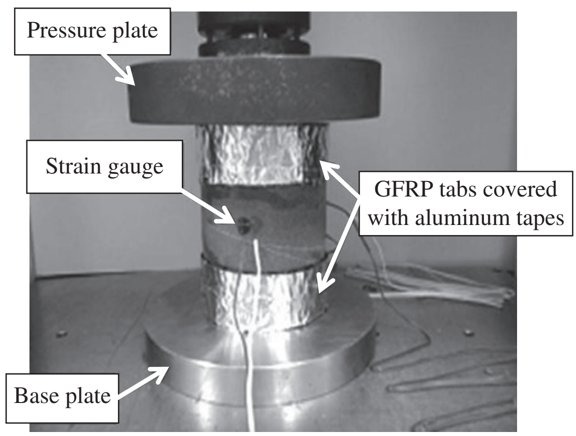


Figure 12. Axial compression test setting.

Table 4. Dimensions of three specimens.

| | No. 1 | No. 2 | No. 3 | Ave. |
|---|---|---|---|---|
| Total length (mm) | 113 | 121 | 118 | 117 |
| Gauge length (mm) | 70 | 70 | 70 | – |
| Outer diameter (mm) | 106.2 | 106.1 | 106.6 | 106.3 |
| Shell thickness (mm) | 3.49 | 3.26 | 3.48 | 3.41 |
| (Standard deviation) | (0.298) | (0.278) | (0.222) | |
| (Coefficient of variation %) | (8.54) | (8.53) | (6.38) | |

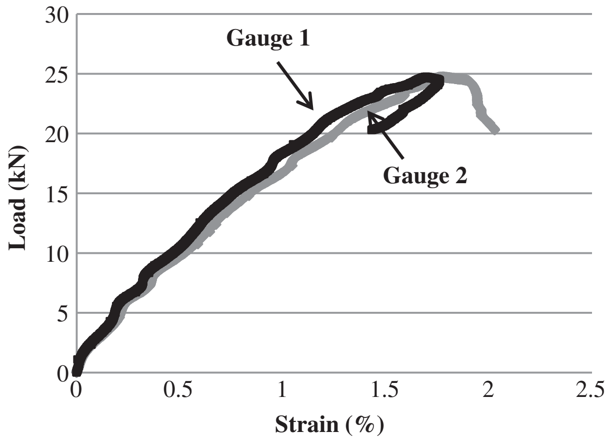


Figure 13. Result of compression test for specimen No. 3.

the average value measured at ten places in circumferential direction. The standard deviations and coefficient of variation of thickness were also listed.

Figure 13 shows the load-strain curves of the No. 3 specimen. The No. 3 cylindrical shell was failed near 25 kN load and the failure mode of cylindrical shell was buckling (Figure 14). Table 5 lists the experimental buckling load, the experimental buckling stress, theoretical buckling stress and the Young's modulus for all the specimens. The theoretical buckling stress was calculated based on Timoshenko's formula (1).[11]

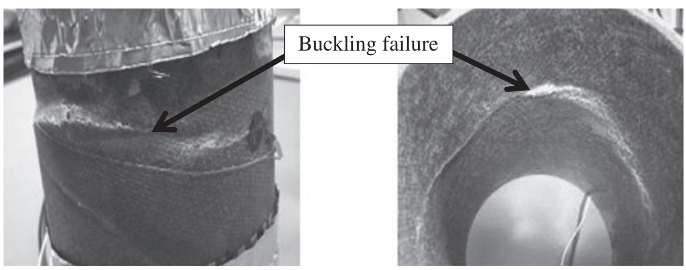


Figure 14. Buckling failure mode of No. 3 specimen.

Table 5. Results of compression test.

| | Young's modulus (GPa) | | | Buckling stress (MPa) | | |
|---|---|---|---|---|---|---|
| | Gauge 1 | Gauge 2 | Buckling load (kN) | $\sigma$ (Experimental) | $\sigma_{cr}$ (Theoretical) | $\sigma/\sigma_{cr}$ (%) |
| No. 1 | 2.0 | 1.5 | 22.9 | 20.3 | 66.4 | 30.6 |
| No. 2 | 1.6 | 1.8 | 19.0 | 18.0 | 62.0 | 29.1 |
| No. 3 | 1.4 | 1.5 | 24.8 | 22.0 | 66.0 | 33.3 |
| Ave. | 1.6 | | 22.2 | 20.1 | 64.8 | 31.0 |

$$\sigma_{cr} = \frac{E}{\sqrt{3(1-\nu^2)}} \times \frac{t}{r} \cong 0.6\,E\frac{t}{r} \quad (1)$$

In which, $E$, $\nu$, $t$ and $r$ are Young's modulus, Poisson's ratio, shell thickness and radius, respectively.

The theoretical buckling stresses were calculated from the dimensions of each cylindrical shell and the Young's modulus calculated as the average value of two gauges (Table 5). From the comparison of both buckling stresses, the average experimental buckling stress of 20.1 MPa was about 31% of the theoretical one (64.8 MPa). Generally speaking, the larger imperfections of cylindrical shells give the smaller experimental buckling load and it is smaller value from 1/3 to 1/2 compared with the theoretical value because of the imperfections. In Table 4, the buckling load of No. 3 cylindrical shell showed the highest value among three specimens because of the smallest coefficient of variation for the thickness among three cylindrical shell specimens.

## 5. Conclusions

(1) The pultrusion molding with fabrics of Kenaf and Linen were possible at 190° of molding temperature and the pultrusion techniques to fabricate PBS/LINEN and PBS/KENAF green composite sheets were developed combined with an extruder.
(2) The tensile strength and the elastic modulus of PBS/LINEN plate were larger than those of PBS/KENAF plate.
(3) The plate laminated with [0–90°/±45°]s of green composite sheets showed the quasi-isotropic mechanical properties and the green composite sheet could be used as an intermediate material. The axial compression test of cylindrical shell fabricated with PBS/LINEN green composite sheets demonstrated the possibility of fabricating other structural elements with PBS/LINEN green composite sheets.



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