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Journal of Reinforced Plastics and Composites 2013 32: 1513 originally published online 24 July 2013
DOI: 10.1177/0731684413498296

Original Article

JOURNAL OF
REINFORCED PLASTICS & COMPOSITES

Journal of Reinforced Plastics and Composites
32(20) 1513–1525

DOI: 10.1177/0731684413498296
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A performance study on composites made from bamboo fabric and poly(lactic acid)

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Abstract

The objective of this study is to investigate the performance of bamboo fabric–poly(lactic acid) composites manufactured by compression moulding. The effects of compression moulding parameters on the mechanical properties of the bamboo fabric–poly(lactic acid) composite sheets were evaluated. Optimum compression moulding parameters to achieve the "best" mechanical properties of the composites was determined using the Taguchi method of experimental design. A rheology test was also conducted to measure the viscosity of the poly(lactic acid) at different temperatures. The processing parameters were found to affect the consolidation and quality of the composites. It appeared that the impact strength of the bamboo fabric–poly(lactic acid) composites in warp direction was enhanced by 240% in comparison to pure poly(lactic acid), whereas the improvements of tensile and flexural properties were lower than expected. When compared with theoretical predictions, the measured values of warp and weft tensile modulus show good agreement than those predicted by rules of mixture. On the other hand, the experimental values of tensile strength were lower than theoretical values due to poor fibre matrix adhesion.

Keywords

Bamboo fabric, poly(lactic acid) sheet, mechanical properties, Taguchi method, compression moulding, green composites

Introduction

The use of biodegradable polymers has become increasingly popular due to growing concerns regarding the impacts of petroleum-based plastics on the environment. It is also regarded as one of the alternatives to minimise the dependency on petroleum-based plastics, especially in packaging applications since this sector is the largest consumer of petroleum-based polymers worldwide.[1] Poly(lactic acid) (PLA) is one of the well-known biodegradable polymers that can be produced in large quantities per year. Motivating factors such as increased availability of PLA and increasing petroleum costs have led to the production of PLA-based biocomposites that can compete with the petroleum-based plastics that are available in the market.[2] PLA is a good candidate for packaging applications because of its good mechanical properties, transparency and biodegradability. However, it has some shortcomings such as low heat distortion temperature, high cost, brittleness and low impact strength.[3] Therefore, PLA can be reinforced with bio-based fibres to produce "green composites" with a profile of promising mechanical properties in comparison to non-renewable petroleum-based products.

Bamboo is one of the most under-utilised natural resources available abundantly in Southeast Asian countries. The total bamboo forest area in the world has reached 22 million hectares currently and worldwide availability of bamboo fibre is over 30 million tonnes per year. Bamboo is one of the fastest growing plants with a maturity cycle of 3–4 years and its fibres

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possess excellent mechanical properties such as high tensile modulus and low elongation at break; their specific stiffness and specific strength are comparable to those of glass fibres. Most of the researches are focused on the composites reinforced with short bamboo fibres;[4–8] however, very few works on the bamboo fabric composites have been published.[9,10] Woven bamboo fabrics possess many excellent properties, such as high tenacity, resistance to bacteria, high strength and stiffness due to continuous yarns oriented in at least two axes.[11] A review of the main mechanical properties of PLA composites reinforced with various types of natural fibres is provided in Table 1.

In this study, the influence of the manufacturing parameters on the mechanical properties of bamboo fabric–PLA prepared via compression moulding method have been investigated by using Taguchi experimental design approach. This method reduces the number of experiments required for investigating the effects of various parameters on the product quality and gives the optimum conditions to achieve the most desirable performance.[23] Although there are some recently published articles on the manufacturing and properties of natural fibre fabric–PLA composites, the application of experimental design for comparative analysis of the effects of manufacturing parameters on the mechanical properties of bamboo fabric–PLA composites have never been reported. In this study, the tensile strength and modulus of the composites were experimentally measured and compared with theoretical calculations.

Materials

PLA sheets of 0.25 mm thickness, manufactured from NatureWorks 2003D, were supplied by Alto Packaging Limited, Hastings, New Zealand. Plain woven bamboo fabric, as shown in Figure 1 (2 warps $\times$ 1 weft), was supplied by Industrial Textiles Limited, Auckland, New Zealand. The yarn thicknesses are 50 tex and 71.4 tex for warp and weft yarns, respectively, while the fabric count is 104 $\times$ 56 per square inch.

Characterisation of bamboo fabric

Bamboo fabric density

Bamboo fabric density was measured in accordance with the ASTM 3800-99 (reapproved 2010) with canola oil as an immersion fluid. This test is also known as Archimedes Test. The bamboo fabric was separated into single yarns and was dried at 60°C for 72 h before the test. The average fibre density was obtained based on the measurement of 10 specimens.

Tensile grab test

Tensile properties of the bamboo fabric were carried out according to ASTM D5034-09 on Instron tensile tester, model 5567. Fabric specimens prepared by the modified tensile grab test method (Figure 2) were characterised in both warp and weft directions. Tensile tests

Table 1. Comparison of the mechanical properties of PLA composites with different reinforcement fibres.

Fibre type and content	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (MPa)	References
Jute (15%)	44	0.88	65	3559	12
Rice straw fibre (30%)	65	–	–	–	13
Cordenka (30%)	58	4.8	–	–	14
Flax (30%)	55	6.31	–	–	14
Recycled newspaper cellulose fibre (30%)	47.7	6.3	113.4	9700	15
Abaca (30%)	74	8.032	124	7890	16
Cellulose (30%)	44	5.846	72	6510	16
Flax (30%)	53	8.3	–	–	17
Jute (40%)	100.5	9.4	–	–	18
Banana fibre (40%)	78.6	7.20	65.4	–	19
Plain weave hemp fabrics (20%)	64	3.2	–	–	20
Twill weaves hemp fabrics (20%)	70	3.5	–	–	20
Kenaf textiles	82.28		–	–	21
Denim fabric (3 layers)	75	4.6	–	–	3
Bamboo fabric (51% fibre volume fraction) weft direction	77.58	1.75	149	1200	9,22
Bamboo fabric (51% fibre volume fraction) warp direction	48.72	0.983	104	2290	9,22

PLA: poly(lactic acid).

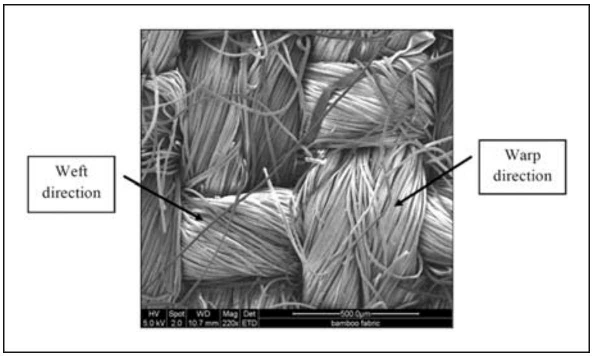

Figure 1. ESEM image of bamboo fabric.
ESEM: environmental scanning electron microscopy.

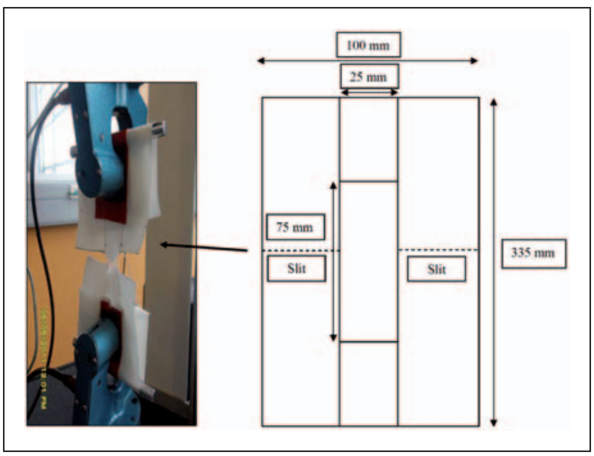

Figure 2. Illustration of modified grab test specimen.

were performed at a gauge length of 75 mm and a cross-head speed of 300 mm/min.

Characterisation of PLA matrix

Differential scanning calorimetry

Differential scanning calorimetry (DSC) (DSC Q1000) analysis was performed to determine the melting point of the PLA sheet. Melting point measurement was conducted on a 9 mg sample in an open aluminium pan under nitrogen atmosphere at 45 ml min^{-1} flow rate in a heating range and rate of 20–250°C and 10°C min^{-1}, respectively.

Rheometer test

The viscosity of the PLA sheet was determined by conducting a rheology test on a PLA sheet sample at three different temperatures, namely 160°C, 170°C and 180°C. These were considered to be suitable consolidation temperatures for natural fibre fabric–PLA composites.[3,9,20] A Universal Dynamic Spectrometer (Physica UDS 200, Paar Physica) was used to measure the viscosity of the polymer. Viscosity (Pa s) was measured as a function of constant increasing shear rate (1–100 1/s); 25 points were measured with measuring point duration of 10 s.

Fabrication of composites

The composite sheets were produced using a film-stacking procedure. The bamboo fabric and the PLA sheets were cut into square pieces of 390 × 390 mm dimension and weighed. The bamboo fabric was dried for 24 h at 80°C in a Moreto vacuum dryer and the PLA sheets were dried overnight at 70°C in a Contherm Thermotec 2000 oven to reduce the moisture content in the materials. Five layers of bamboo fabric oriented in the warp direction and six layers of PLA sheets were arranged alternately with each other in a stack, as shown in Figure 3. This resulted in a fibre weight fraction of 0.35 (0.34 fibre volume fraction) and 2.1 mm thickness. The authors found that composites from flax yarn and PLA matrix of 35% fibre volume fraction possessed excellent formability characteristics.[24] Since the thermoforming process will be conducted on the composite sheets to produce the packaging products for future work, the fibre volume fraction in the range closest to 35% was chosen in this study. A square mould of dimensions 400 × 400 mm, placed inside a 100 t hydraulic press, was heated using electrical and oil heaters to 160°C. A thermocouple was placed outside the mould in order to monitor its temperature. Once the mould reached a temperature of 160°C, the upper platen was opened and the bamboo fabric–PLA stack was quickly placed inside the mould. Then, the mould was closed without pressure for first 2 min to allow permeation of the polymer through the fabric, followed by the application of pressure and heating time according to the experimental design requirements. The temperature was held at 160°C; after the set heating time, the mould was cooled by circulating cold water. The composite was kept under the set pressure until it cooled to 25°C. The platen was opened and the composite was removed from the press.

Mechanical properties

Three different mechanical tests were conducted in this study to test composite sheet properties, namely tensile, flexural and Charpy impact test. For each test, seven replicate test specimens were taken and the averages and corresponding maximum standard deviation were calculated.

Tensile properties

Tensile properties of bamboo fabric–PLA composites were characterised in accordance with ASTM D638-10.

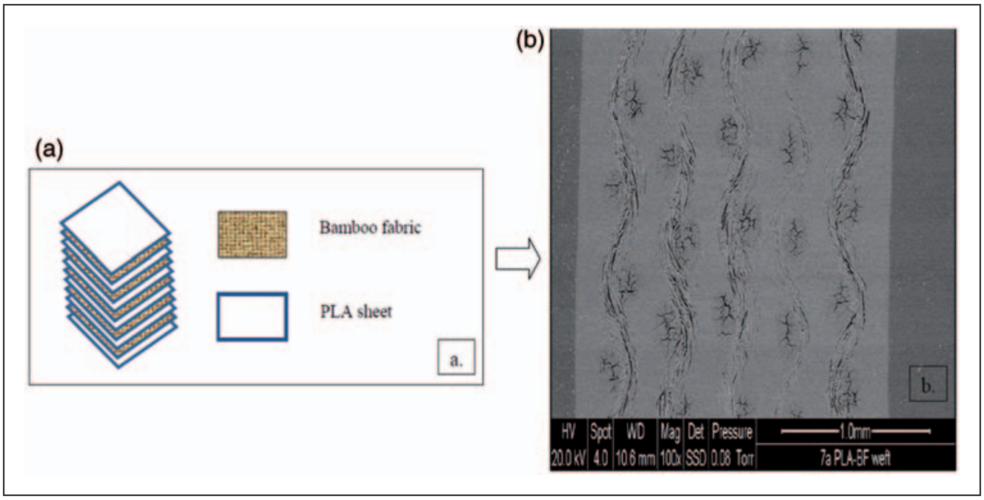

Figure 3. (a) Arrangement of bamboo fabric and PLA sheets in the stack and (b) cross-section of the bamboo fabric–PLA composites.
PLA: poly(lactic acid).

Samples for tensile testing were cut according to Type I specimens. Tensile tests were carried out using a universal mechanical testing machine (Instron model 5567). The machine was operated at a crosshead speed of 5 mm/min and a gauge length of 50 mm.

Flexure properties

Flexural test was conducted as per ASTM D 790-10. Samples for flexural testing were cut into rectangular strips with dimensions of approximately $12.7 \times 75 \times 2.1$ mm. Specimens were loaded in three-point bending with a recommended span to depth ratio of 16:1. Tensile tests were carried out using a universal mechanical testing machine (Instron model 5567). The machine was operated at a crosshead speed of 10 mm/min.

Impact properties

The impact resistance of bamboo fabric–PLA composite was determined using flatwise notched test specimens prepared according to ASTM D 6110-10. A Ceast pendulum impact tester with a 1 J hammer was used. Samples for impact testing were cut into rectangular strips of $125 \times 12.7 \times 2.1$ mm. A 45° V-shaped notch was made at the central part of the impact bar by a razor notching machine (CEAST) with a notch-tip radius of 0.25 mm. The depth of the specimen remaining under the notch was 10.16 mm.

Environmental scanning electron microscopy

Bamboo fabric, tensile fracture surfaces and cross-section of the composite samples were vacuum coated with gold by evaporation before examination and then analysed using environmental scanning electron microscopy (ESEM) (FEI Quanta 200F ESEM).

Design of experiment using the Taguchi method

The Taguchi method used for the design of experiments considered two control factors, namely consolidation pressure and time. Each parameters was assigned at three levels (low, 1; medium, 2 and high, 3) while the tensile, flexural and impact properties were chosen as the responses.

Consolidation parameters selection

Consolidation pressure

Low: 0.39 MPa; medium: 0.66 MPa and high: 1.05 MPa. A 1.05 MPa consolidation pressure was chosen due to the maximum allowable pressure of the press. The lower limit was restricted to 0.39 MPa because during the pre-experimental phase, any consolidation pressures lower than this showed problem in consolidation. A 0.66 MPa consolidation pressure was chosen as the intermediate value.

Consolidation time

Low: 3 min; medium: 5 min and high: 10 min. The consolidation time was chosen based on the literature review for natural fibre–PLA composites (as shown in Table 1) and according to pre-experimental findings. The relative viscosities of PLA can be expected to differ at different consolidation times, possibly a result of different morphologies and therefore different mechanical properties. The higher limit (10 min) was restricted with regard to concerns that PLA may begin to degrade at longer consolidation times. The lower limit (3 min) was set due to economic reasons at the selected consolidation temperature (160°C), while 5 min was chosen as the intermediate value.

Theoretical aspects

Evaluation of elastic properties by rule of mixture

The elastic properties of unidirectional bamboo lamina were predicted from fibre and matrix properties (Table 2) using simple rule of mixture relationships from the mechanics of materials approach. From these values, the elastic properties of woven bamboo fabric ply were predicted by using the following relations[26]

$$E_{11} = KE_1 \tag{1}$$

$$E_{22} = (1 - K)E_1 \tag{2}$$

where E_1 is the Young's modulus of bamboo fibre and E_{11} and E_{22} are Young's modulus in warp and weft directions, respectively.

The factor K is defined by $K = \frac{t_1 N_1}{t_1 N_1 + t_2 N_2}$, where N_1 and N_2 are the number of yarns in warp and weft directions, respectively, while t_1 and t_2 are the thickness of yarns in warp and weft directions, respectively.

For bamboo fabric, $N_1 = 104$ and $N_2 = 56$. Hence, $K = 0.565$. The bamboo fabric volume fraction V_f was calculated using the following equation

$$V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f} \tag{3}$$

where V_f is the volume fraction of bamboo fabric, W_f is the weight of bamboo fabric, W_m is the weight of matrix, ρ_f is the density of bamboo fabric and ρ_m is the density of matrix.

The volume fraction of bamboo fabric is 0.34. Elastic properties of composites were determined using the rule of mixture. The proposed rule for elastic properties of laminates is given by the following expression

$$E_c = E_f\, V_f + E_m\, V_m \tag{4}$$

Table 2. Properties of bamboo fibre and PLA matrix.[a]

Property	Bamboo fibre		PLA
	Warp	Weft	
Density (g/cm^3)	1.3 (0.06)		1.25 (0.06)
Young's modulus (GPa)	18.5[25]		3.38 (0.075)
Breaking force (N)	649 (34.91)	355 (21.82)	–
Yarn thickness (tex)	50	71.4	–
Tensile strength (MPa)	271.32[b]	176.09[b]	61.85 (2.218)

[a]Standard deviation values are given in parentheses.
[b]Calculated from tensile grab test values.
PLA: poly(lactic acid).

Evaluation of tensile strength by rule of mixture

The tensile strength of unidirectional bamboo lamina were predicted from fibre and matrix properties (Table 2) using simple rule of mixture relationships from the mechanics of materials approach. From these values, the tensile strength of woven bamboo fabric ply was predicted by using the following relations[27]

$$\sigma_{11} = \frac{F_1}{N_1 A_1} \tag{5}$$

$$\sigma_{22} = \frac{F_2}{N_2 A_2} \tag{6}$$

where F_1 is the breaking force of warp yarn, F_2 is the breaking force of weft yarn, A_1 is the area of the warp yarn cross-section, A_2 is the area of weft yarn cross-section, σ_{11} and σ_{22} are tensile strengths of bamboo yarn in warp and weft directions, respectively, and N_1 and N_2 are the number of yarns in warp and weft directions, respectively, that break between 25 mm width of bamboo fabric during the tensile grab test (see Figure 2). For bamboo fabric, $N_1 = 104$ yarns and $N_2 = 56$ yarns. The area of bamboo yarns were measured from bamboo fabric lamina cross-sections ESEM images using imageJ software. Figure 4(a) and (b) shows the ESEM images of the bamboo yarns for warp and weft directions, respectively. For the bamboo yarn area, $A_1 = 0.023\,\text{mm}^2$ and $A_2 = 0.036\,\text{mm}^2$. The volume fraction of bamboo fabric is 0.34. To calculate the tensile strength of the composite, it is essential to determine which component, fibre or matrix, has the lower failure strain. The failure strain of the fibre and matrix are defined by

$$\varepsilon_{11} = \sigma_{11}/E_1 \tag{7}$$

$$\varepsilon_{22} = \sigma_{22}/E_1 \tag{8}$$

$$\varepsilon_m = \sigma_m/E_m \tag{9}$$

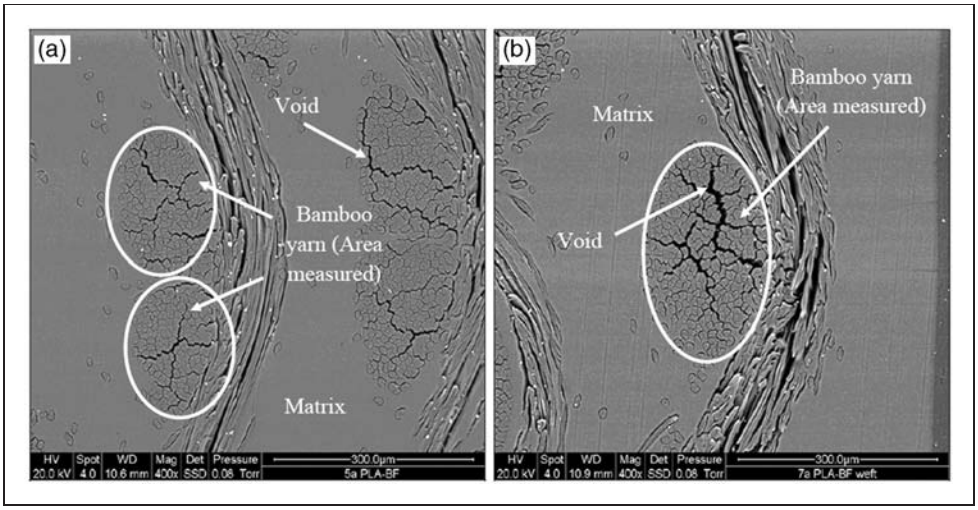

Figure 4. Bamboo fabric–PLA composite cross-sections in the: (a) warp and (b) weft directions.
PLA: poly(lactic acid).

where ε_{11}, ε_{22} and ε_m are the failure strains of bamboo yarn in warp and weft directions and in PLA matrix, respectively.

$\varepsilon_f < \varepsilon_m$ fibres fail first. At that strain, assuming a linear stress–strain curve for the PLA matrix, the matrix strength is

$$\sigma'_m = E_m \, \varepsilon_f \tag{10}$$

Tensile strength of composites was determined using rule of mixtures. The proposed rule for tensile strength of laminates is given by the following expression[28]

$$\sigma_c = \sigma_f V_f + \sigma'_m V_m \tag{11}$$

The above rule has some important underlying assumptions. These are listed in the following: (a) the fibres are uniformly distributed within the matrix, i.e. there are no fibre-rich or matrix-rich regions in the composite; (b) there is perfect bonding between the matrix and the fibres; (c) the composite is free of voids and (d) both the fibres and the matrix behave as perfectly linear elastic materials.

Results and discussion

Characterisation of bamboo fabric

Table 2 shows the density and breaking force of bamboo fabric in warp and weft directions. The measured density of the bamboo fabric, $1.3\,\mathrm{g/cm^3}$, is in good agreement with the density of bamboo fibre reported in the literature.[25] The breaking force of the bamboo fabric in warp direction was higher compared with that in the weft direction. This is because bamboo fabric is not completely symmetrical in that there are more fibres in the warp direction compared to weft direction. In the warp direction, there were 1.86 times more yarns than in the weft direction. The obtained breaking force was used to determine the tensile strength of the bamboo fabric. The density and tensile strength of the bamboo fabric obtained were also used for theoretical predictions section of this article.

Characterisation of PLA matrix: DSC

Figure 5 shows the endothermic curves for PLA. The melting and glass transition temperature, T_m and T_g, peaks for the PLA were 152°C and 58°C, respectively. The T_g and T_m range obtained in this study are in close agreement with earlier observations reported for PLA.[29] Hence, the viscosity of PLA at temperatures higher than 152°C was studied to discover suitable consolidation temperature to be applied throughout the compression moulding process.

Rheology

Figure 6 shows that the viscosity of the PLA polymer decreases drastically as the shear rate increases. During film stacking process, the polymer has to migrate through and trap the fibres without displacing them. Bodros et al.[30] reported that the viscosity of a polymer used in a film stacking process had to be close to 100 Pa s for better impregnation of the fibres. This value is reached for the PLA matrix used between temperatures of 160°C and 180°C. Figure 6 also shows that there is no significant difference in viscosity of PLA between 160°C and 180°C. Therefore, the consolidation temperature of 160°C was chosen in this study in order to reduce the manufacturing energy requirements and thus the cost.

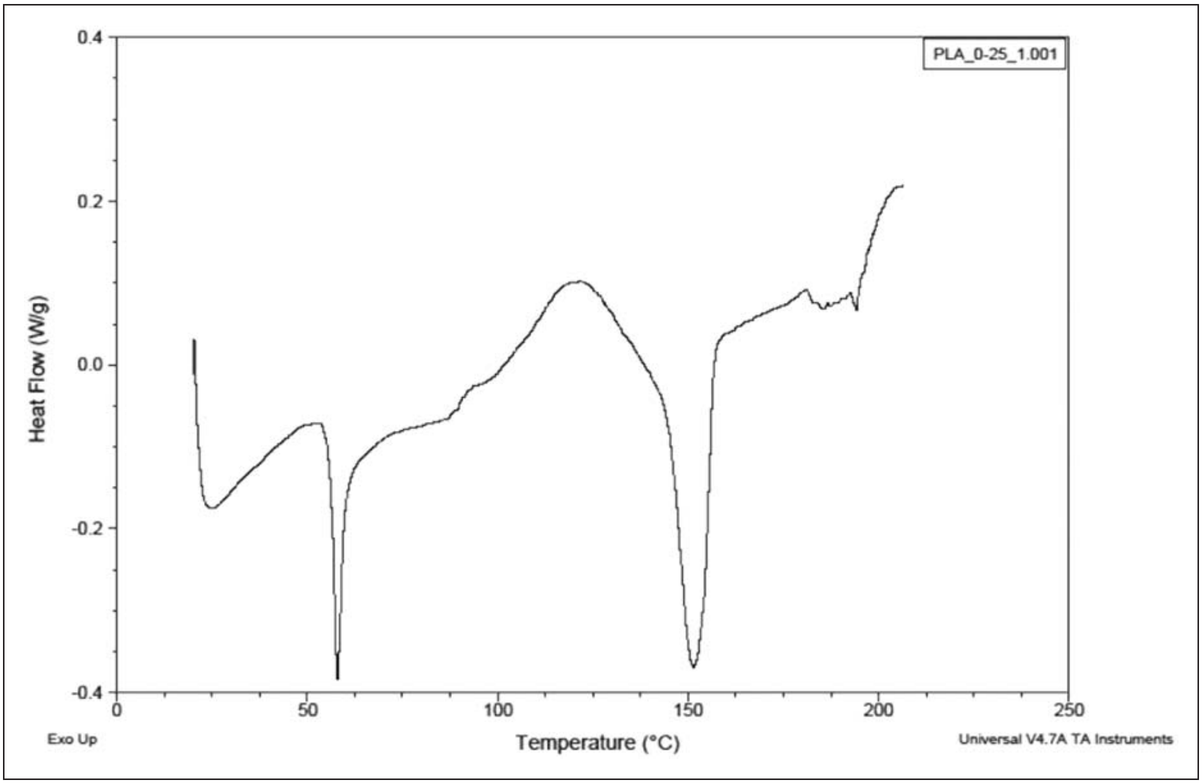

Figure 5. Endothermic curve for PLA obtained using DSC analysis.
PLA: poly(lactic acid); DSC: differential scanning calorimetry.

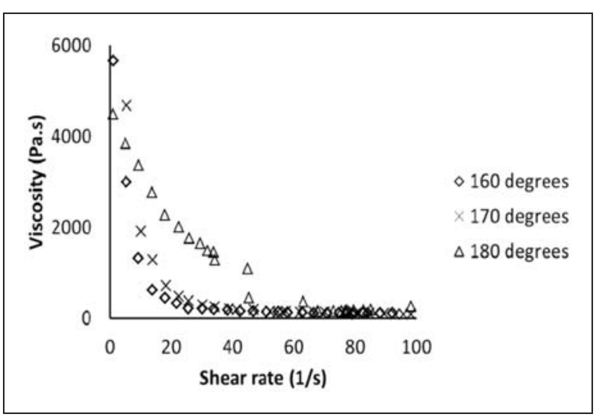

Figure 6. The viscosity of PLA as a function of shear rate at different temperatures.
PLA: poly(lactic acid).

Mechanical properties

The results of the mechanical properties obtained from L9 Orthogonal arrays are shown in Table 3. The tensile properties of bamboo fabric–PLA composites in the warp direction demonstrated higher mechanical properties compared with the weft direction. This is attributed to the difference of breaking force in both directions as also observed in previous studies[9,31]: the warp direction has a higher breaking force (649 N) compared with the weft direction (355 N). Kawabata[32] supported this finding by stating that tensile strength of a woven fabric is the same as that of the sum of the strengths of the yarns oriented along the tensile direction.

A flexure test typically induces tensile, compressive and shear stresses simultaneously. Therefore, the observation made earlier for the tensile strength and the effect of the fabric direction are also clearly seen here. The warp direction of the bamboo fabric has a remarkable effect on the flexural modulus, similar to the observation made for its tensile properties.

The superior impact property of bamboo fabric–PLA composites is due to crack propagation in the composites. In the case of the fabric-reinforced composites, the cracks can be deviated at the crossover points of the fabric. As a result, fabric-reinforced composites have higher impact properties as compared with the short fibre composites[17] and unidirectional fibre composites.[16]

Taguchi analysis

The orthogonality of the Taguchi experimental design method makes it possible to separate the effects of each

Table 3. Orthogonal array L9 (3^2) of the experimental runs and results.[a]

Run	Control factors		Tensile strength (MPa)		Tensile modulus (GPa)		Flexural strength (MPa)		Flexural modulus (GPa)		Impact strength (J/m)	
	Pressure (MPa)	Time (min)	W	F	W	F	W	F	W	F	W	F
1	0.39	3	83.09 (3.22)	57.61 (2.14)	5.69 (0.39)	3.72 (0.30)	118 (2.83)	113 (2.73)	4.01 (0.03)	3.78 (0.13)	141.13 (13.04)	110.14 (10.44)
2	0.39	5	76.6 (1.17)	56.51 (0.74)	5.18 (0.21)	3.74 (0.26)	122 (5.76)	113 (4.25)	3.92 (0.33)	3.73 (0.19)	132.25 (10.75)	98.2 (5.32)
3	0.39	10	81.16 (1.17)	62.26 (1.39)	5.81 (0.24)	4.91 (0.19)	127 (6.91)	124 (2.11)	4.17 (0.36)	4.23 (0.11)	109.23 (4.42)	94.42 (24.35)
4	0.66	3	80.71 (1.05)	59.1 (1.01)	5.42 (0.17)	4.32 (0.11)	124 (3.41)	119 (3.25)	4.11 (0.06)	4.01 (0.10)	123.49 (12.79)	97.97 (11.46)
5	0.66	5	82.46 (1.17)	61.58 (0.17)	5.54 (0.23)	4.26 (0.12)	127 (1.41)	118 (2.65)	4.31 (0.03)	3.93 (0.12)	121.55 (11.73)	94.68 (6.79)
6	0.66	10	81.61 (2.28)	62.89 (0.84)	5.72 (0.17)	5.15 (0.20)	131 (2.81)	120 (3.74)	4.55 (0.19)	4.15 (0.24)	112.19 (10.92)	83.36 (12.64)
7	1.05	3	80.68 (2.24)	60.75 (1.05)	5.82 (0.16)	4.25 (0.07)	128 (3.57)	117 (1.54)	4.13 (0.29)	4.03 (0.13)	127.61 (8.47)	94.91 (10.29)
8	1.05	5	81.29 (0.35)	60.49 (1.10)	6.1 (0.51)	4.52 (0.16)	125 (3.31)	120 (0.96)	4.27 (0.27)	4.18 (0.08)	126.64 (9.87)	92.17 (8.12)
9	1.05	10	79.32 (2.59)	63.72 (0.56)	5.78 (0.38)	5.00 (0.14)	129 (4.71)	122 (2.22)	4.33 (0.16)	4.2 (0.20)	119.94 (11.87)	91.43 (5.90)
Pure PLA			61.85 (2.22)		3.38 (0.08)		105 (5.35)		3.72 (0.05)		37.51 (5.35)	

[a]Standard deviation values are given in parentheses.
W: warp; F: weft; PLA: poly(lactic acid).

consolidation parameters at different levels using the average of experimental outputs. The Taguchi orthogonal array L9 (3^2) with three logical levels for each parameter was used in this study. The two parameters identified as processing factors affecting tensile, flexural and impact properties were consolidation pressure and time, at a constant temperature of 160°C. Herein, analyses of the effects of consolidation parameters were conducted on the average values of tensile, flexural and impact properties outputs using response table and graphs. The calculated average values shown in the response table and graphs can be used to identify the optimal set of conditions to achieve the greatest performance of the bamboo fabric–PLA composite sheets. The factor settings at highest values were considered the optimum set of process conditions. An example of the response table is shown in Table 4.

Figure 7 illustrates the response graph from Taguchi analysis of the average values of tensile strength and modulus in the weft and warp directions. The figure shows that the highest pressure and longest time resulted in maximum values for tensile strength in weft direction and tensile modulus for both warp and weft directions. On the other hand, for the case of tensile strength in the warp direction, Figure 7(a) shows that medium pressure and shortest time resulted in highest values for tensile strength. However, the small difference between the longest (10 min) and shortest (3 min) average values for the consolidation time from response graphs indicates that the effect of this parameter on tensile properties is trivial.

Likewise, the same trend are also indicated for the response graph of flexural strength and modulus, as shown in Figure 8, where the small difference of the response values resulting from the longest and shortest time is less than 10%. Therefore, 3 min was chosen for the manufacturing time as short processing time offers better cost and production efficiency. The results from Figures 7 and 8 also suggested that the extent of impregnation of the matrix inside the fabric is very dependent on the pressure applied, with highest pressure (1.05 MPa) giving better tensile and flexural performance of the composites.[33]

With regards to impact strength, as shown in Figure 9, it appears that 0.39 MPa consolidation pressure and 3 min consolidation time gives the highest values for impact strength. This is somewhat contrary to the parameters obtained for tensile and flexural properties. This is likely due to the theory that more energy will be absorbed when there is poor adhesion between matrix and fibre.[14,34] Brady and Kardos[35] also mentioned that generally for continuous fibre-reinforced brittle matrices, it might be implied that as the degree of adhesion increases, the toughness should decrease. Analysis of the results leads to the conclusion

Table 4. Response graph for flexural modulus (warp direction).

Random order trial number	Standard order trial number	Response observed values, *Y*	Consolidation pressure (MPa)			Consolidation time (min)		
	1	3626	3626			3626		
	2	3924	3924				3924	
	3	4172	4172					4172
	4	4112		4112		4112		
	5	3867		3867			3867	
	6	4550		4550				4550
	7	4125			4125	4125		
	8	4272			4272		4272	
	9	4331			4331			4331
Total		9						
Number of values		36,979	11,722	12,529	12,728	11,863	12,063	13,053
Average		4109	3907	4176	4243	3954	4021	4351

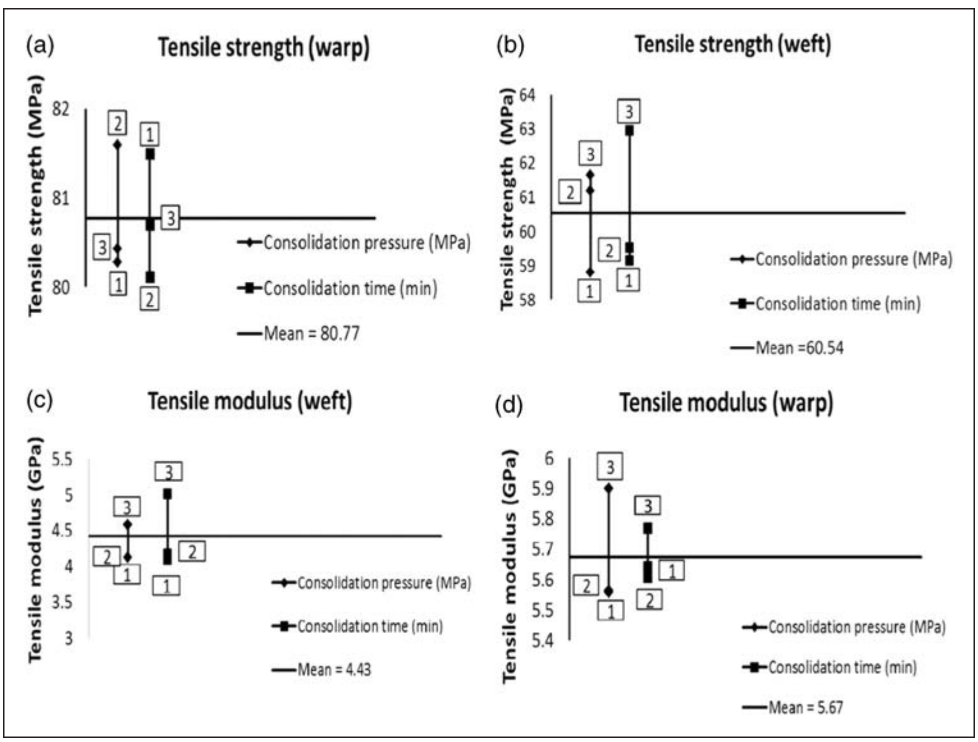

Figure 7. Response graphs from Taguchi analysis on average values of tensile strength for: (a) warp and (b) weft directions and tensile modulus for: (c) weft and (d) warp directions of bamboo fabric–PLA composites.
PLA: poly(lactic acid).

that the optimum condition for each response is unlikely to be equal to the optimum condition for the other responses.

Confirmation test

Confirmation experiments were carried out to determine the processing conditions to obtain the desirable mechanical properties of the composites. These conditions were compared with those obtained from the Taguchi analysis. Such experiments are important to confirm the validity of the Taguchi analysis method to determine optimum processing conditions for "best" mechanical properties of the composites. The results of these confirmation experiments are shown in Table 5. It was found that tensile and flexural

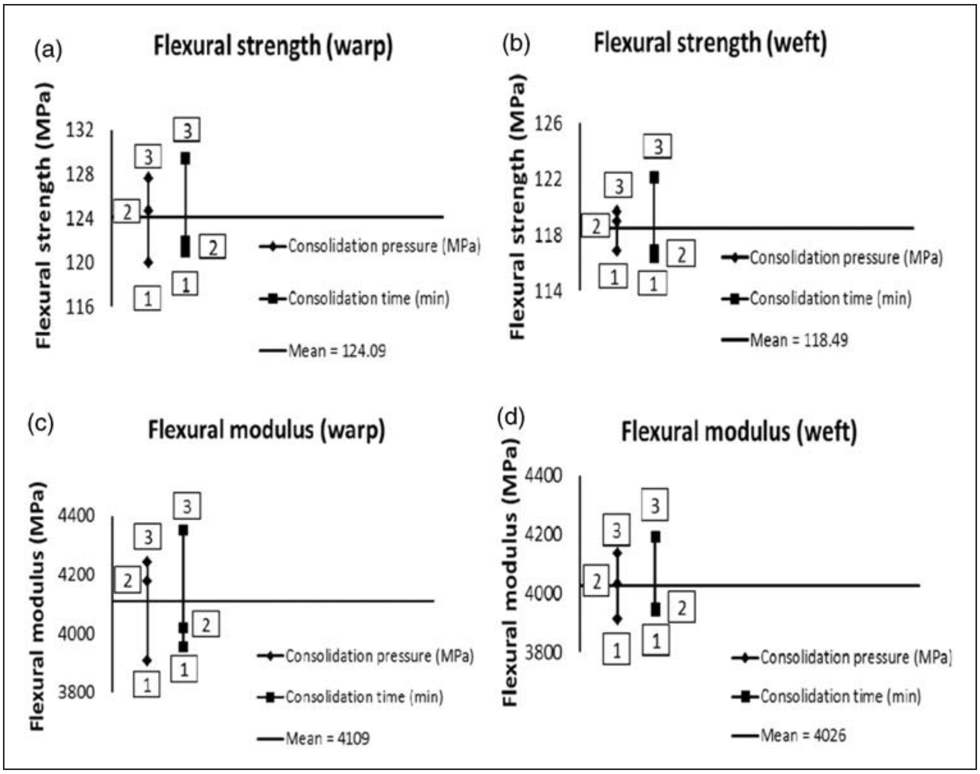

Figure 8. Response graphs from Taguchi analysis on average values of flexural strength for: (a) warp and (b) weft directions and flexural modulus for: (c) warp and (d) weft directions of bamboo fabric–PLA composites.
PLA: poly(lactic acid).

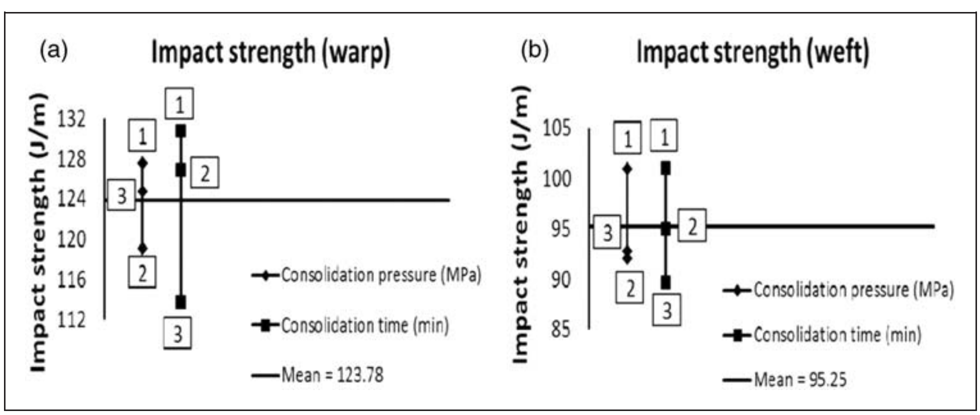

Figure 9. Response graphs from Taguchi analysis on average values of impact strength for: (a) warp and (b) weft directions of bamboo fabric–PLA composites.
PLA: poly(lactic acid).

modulus of the bamboo fabric–PLA were improved by 240% and 96%, respectively, compared with those reported in the literature[9] after optimisation using the Taguchi method, even though the breaking forces of the bamboo fabric used in their study were greater compared with the bamboo fabric used in this study.

The comparison between experimentally measured and predicted values of tensile strength and modulus are shown in Table 6. The predicted values were calculated based on simple rule of mixture. For tensile modulus, Table 6 shows good agreement between experimentally measured and predicted values in which the differences are only between 2% and 4%.

Table 5. Optimum conditions and the measured mechanical properties from confirmation test.[a]

	Tensile modulus (GPa)	Tensile strength (MPa)	Flexural modulus (GPa)	Flexural strength (MPa)	Impact strength (J/m)
Temperature = 160°C, Pressure = 1.05 MPa, Time = 3 min					
Warp	5.919 (0.26)	80.64 (1.80)	4.495 (0.70)	143 (1.59)	103 (6.68)
Weft	5.170 (0.19)	61.93 (2.17)	4.094 (0.63)	128 (1.04)	91.68 (8.42)
Temperature = 160°C, Pressure = 0.39 MPa, Time = 3 min					
Warp	5.259 (0.18)	80.89 (2.06)	4.184 (0.12)	132 (0.82)	126 (6.82)
Weft	4.591 (0.47)	57.84 (0.41)	3.494 (0.14)	115 (0.90)	103 (3.58)

[a]Standard deviation values are given in parentheses.

Table 6. Comparison of experimental and theoretical tensile properties of bamboo fabric–PLA composites based on rule of mixture.

Composites	Measured tensile strength (MPa)	Theoretical tensile strength (MPa)	Change (%)	Measured tensile modulus (GPa)	Theoretical tensile modulus (GPa)	Change (%)
Bamboo fabric–PLA (warp)	80.6	125.14	−35.6	5.92	5.78	2.4
Bamboo fabric–PLA (weft)	61.9	80.96	−23.5	5.17	4.97	4.0

PLA: poly(lactic acid).

However, the measured values for tensile strength were 36% and 24% lower than theoretical values in the warp and weft directions, respectively. Such deviation is due to the fact that the rule of mixture disregards the fibre matrix bonding, void contents and the contribution of variations in fibre alignment.[36] Lee et al.[3] stated that the failure of the resin occurred first, followed by the yarn failure during the tensile test, as supported by observations of resin cracks before the final failure of the composites. Once cracks are initiated and propagated in the resin, shear stress is focused on the interface between fibres and matrix. Interfacial adhesion between fibres and matrix is predominantly responsible for tensile strength. Many researchers claimed that poor tensile strength of natural fibre-reinforced composites is caused by poor matrix and fibre interaction.[18,37–39] The ESEM image of the fractured surface displayed in Figure 10 showed deprived adhesion between the resin and fabric in the bamboo fabric–PLA composite and this factor is considered as a reason for less pronounced tensile property improvement than predicted. This finding also showed that the composites manufactured by this compression moulding method contain some voids. Microscopy images shown in Figure 4(a) and (b) confirmed the presence of voids inside the bamboo yarns. Besides, this deviation can always be expected in bamboo fabric composites due to non-uniformity of bamboo yarns.

On the other hand, the impact strength results indicated 240% improvement in the warp direction when compared with pure PLA. In terms of mechanical properties, the warp direction presented excellent energy absorption capabilities and can overcome the low impact strength of PLA, which is known as its limitation. The impact strength of bamboo fabric–PLA composites also showed greater performance than the denim fabric-reinforced PLA.[3] Furthermore, the

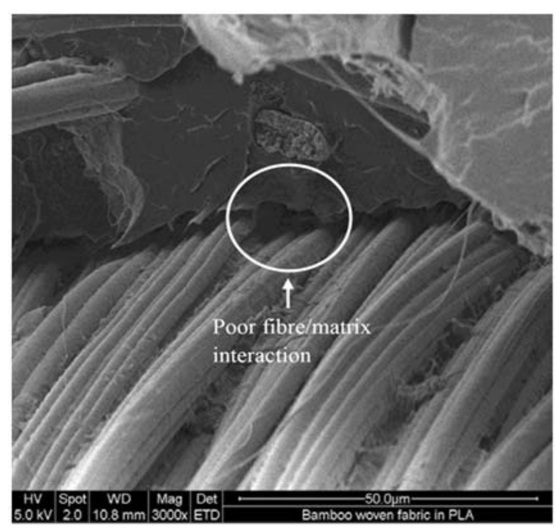

Figure 10. ESEM image of fracture surfaces of bamboo fabric–PLA composites.
ESEM: Environmental scanning electron microscopy; PLA: poly(lactic acid).

bamboo fabric–PLA composites showed superior tensile and flexural properties than those of bamboo fabric–polypropylene composites.[10] This suggested that PLA has a potential to substitute polypropylene in packaging applications.

Conclusions

The effects of compression moulding processing parameters on the mechanical properties of the bamboo fabric–PLA composites were successfully analysed using Taguchi experimental design approach. Analysis of the results obtained from the confirmation test leads to the conclusion that the combination of highest pressure (1.05 MPa) and shortest time (3 min) gives desirable tensile and flexural properties. Meanwhile, the combination of lowest pressure (0.39 MPa) and shortest time (3 min) gives desirable impact strength. Hereby, the combination of highest pressure and shortest time were chosen as optimum conditions for the compression moulding process because these parameters resulted in desirable tensile and flexural properties and acceptable impact performance of the bamboo fabric–PLA composite sheets. The impact strength of the bamboo fabric–PLA composites in warp direction was enhanced 240% compared with pure PLA, whereas the improvement of tensile and flexural properties were less than expected. Simple rule of mixture can be conveniently used for predicting the tensile strength and modulus of bamboo fabric–PLA composites. The experimental values obtained for tensile strength were lower than theoretical values due to poor fibre matrix adhesion and presence of voids inside the bamboo yarns.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgments

This work is supported by Universiti Sains Malaysia (USM) and Ministry of Higher Education (MOHE), Malaysia, through scholarships to the first author. Thanks also go to the staff at the Centre for Advanced Composite Materials, The University of Auckland, New Zealand.

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