Evaluation of Mechanical Properties in Biodegradable Composites Reinforced with a Natural Fiber

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Abstract

In the present study, we use a bamboo fiber as the reinforcement and polybutylenesuccinate (PBS) as the matrix. We fabricate long fiber unidirectional composites and cross-ply laminate with different fiber volume fractions (10, 20, 30, 40 and 50wt%). We conduct tensile tests on those composites and evaluate the mechanical properties. In addition, we measure the bamboo fiber strength distribution. We discuss experimentally-obtained properties based on the mechanical properties of constituent materials. Then, we obtain following results.

Young's modulus and tensile strength in BF/PBS increase with increasing fiber weight fraction. However, the strain at fracture showed decreasing trend. Young's modulus in BF/PBS is predictable by the rules of mixture. Composites tensile strength is lower than Curtin's prediction of strength which considers distribution of fiber strength.

1. Introduction

Plastics have played significant role in the development of the society because of their versatile nature. However, non-biodegradable nature of plastics presents various challenges to environment. Incineration of plastics produces harmful gases. Persistent nature of plastics makes limited land filling sites full. From necessity of eco-friendly materials, biodegradable plastics have been developed. Biodegradable plastics can be produced from recyclable resources, so their materials can be used without destruction of environment. For this reason, these materials have attracted a lot of attention as substitutes of conventional plastics[1]. However, many of them have lower mechanical properties than conventional plastics. Therefore, there are many studies to improve the properties of these materials for industrial applications. Natural fiber possesses high specific strength and stiffness due to their low density. Therefore, reinforcing biodegradable plastic with a natural fiber is an effective method without a loss of its biodegradability. On such materials, only some combinations of fibers and matrices have been tried and the properties of them are not well understood. In the present study, we use a bamboo fiber as the reinforcement and polybutylenesuccinate (PBS) as the matrix. We fabricate long fiber unidirectional composites and cross-ply laminates ($[0/90]_s$) with different fiber volume fractions (10, 20, 30, 40 and 50wt%). We conduct tensile tests on those composites and evaluate the mechanical properties. In addition, we measure fiber strength distribution[2]. We discuss experimentally-obtained properties based on the mechanical properties of constituent materials. Young's modulus and tensile strength in unidirectional composite are discussed through the rules of mixture and Curtin's composite strength prediction analysis, respectively. Also Young's modulus and Poisson's ratio in cross-ply laminate are discussed through the laminate theory.

2. Experimental method

2.1 Materials and composite fabrication

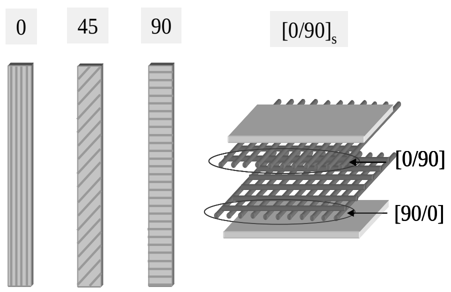
We use bamboo fibers (Ban, Ltd., Tokushima, Japan) as reinforcement and PBS (Showa High Polymers, Ltd., Tokyo, Japan) is used as matrix. We fabricate long fiber unidirectional composites and cross-ply laminate ($[0/90]_s$) using these materials. Hereinafter, those composites are called BF/PBS.

2.2 Composite fabrication

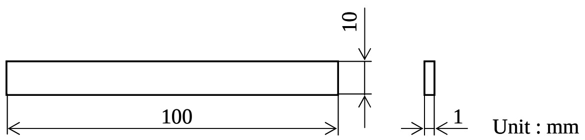
We fabricate unidirectional composites and cross-ply laminates with different fiber weight fractions (10, 20, 30, 40 and 50 wt%), using a hot press (Imoto corporation, Ltd., Kyoto, Japan)[3]. During processing, the materials were kept at 150℃ and pressed for 10 min. at a pressure of 10MPa. After that, specimens were cooled naturally in the air. Fig.1 shows schematic specimen configuration. Unidirectional composites and cross-ply laminates are in the same configuration. Specimen size was 100mm long, 10mm wide and 1mm thick.

2.3 Tensile test

Tensile tests are performed on the composite specimens and the bamboo fibers at a crosshead speed of 0.5mm/min and tensile load is applied until specimen final fracture. After tensile test for fibers, the fracture surface is observed by using an SEM and the cross sectional area is measured.



(a) Schematic of specimens



(b) Specimen configuration

Fig.1 Composite specimen for tensile test

3. RESULTS AND DISCUSSIONS

3.1 Tensile test on bamboo fibers

All bamboo fibers showed brittle fracture behavior in which the load increased proportionally with time and suddenly dropped at the final fracture. To characterize the fiber strength distribution[4], we used Weibull function which can be expressed by the following equation

$$F(\sigma) = 1 - \exp\left\{ -\left(\frac{D}{D_0}\right)^2 \left(\frac{\sigma}{\sigma_0}\right)^m \right\} \qquad (1)$$

where F is the fracture probability at stress σ, D and D_0 are the specimen and reference fiber diameter, respectively, m is the shape parameter and σ_0 is the scale parameter. By Weibull plotting based on equation (1), we obtained Weibull parameters m and σ_0 which are listed in Table 1. Fig.2 shows the resulting Weibull plot of bamboo fibers. We used median rank method for cumulative fracture probability F(σ). Fig.3 shows relation between tensile strength and diameter in bamboo fiber. A large scatter is found in both fiber diameter and strength distribution.

Table 1 Mechanical properties in bamboo fiber

Number of samples	92
Shape parameter m	3.41
Scale parameter σ_0 (MPa)	415
Average Young's modulus (GPa)	19.2

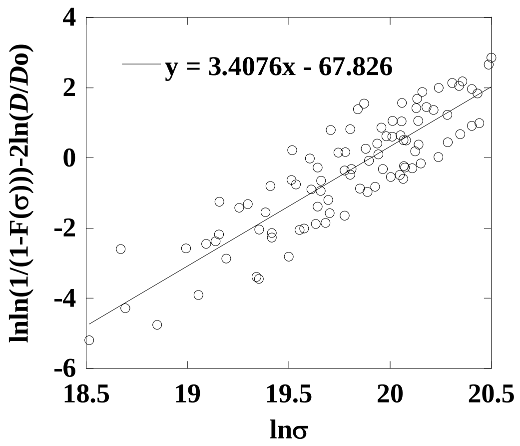


Fig.2 Weibull plot results in bamboo fiber.

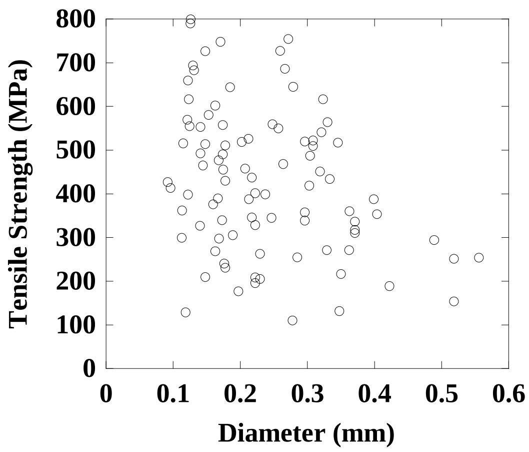


Fig.3 Relation between tensile strength and fiber diameter in bamboo fibers.

Table 2 Mechanical properties in the fiber direction

	Young's modulus (GPa)	Tensile strength (MPa)	Longitudinal strain at fracture (%)
10wt%	3.08	43.2	1.118
20wt%	6.15	55.6	0.885
30wt%	10.74	90.7	0.995
40wt%	12.64	78.4	0.772
50wt%	13.54	95.6	0.897

Table 3 Mechanical properties in 45 degree direction

	Young's modulus (GPa)	Tensile strength (MPa)	Longitudinal strain at fracture (%)
10wt%	1.72	13.48	1.05
20wt%	2.1	10.72	0.882
30wt%	2.55	11.03	0.728
40wt%	2.33	7.12	0.357
50wt%	2.78	10.5	0.385

Table 4 Mechanical properties in the transverse direction

	Young's modulus (GPa)	Tensile strength (MPa)	Longitudinal strain at fracture (%)
10wt%	1.06	7.09	0.664
20wt%	1.63	7.38	0.502
30wt%	1.9	6.29	0.385
40wt%	2.4	4.15	0.18
50wt%	2.33	6.16	0.289

3.2 Tensile test in fiber direction

Fig.4 shows stress-strain curves for BF/PBS unidirectional composite in the fiber direction. Mechanical properties in the fiber direction are listed in Table 2. It is found that Young's modulus increases with increasing fiber weight fraction but the strain at fracture shows decreasing tendency. Tensile strength increases with increasing fiber weight fraction for 10, 20 and 30wt% but there is small difference among 30 - 50 wt%. Although there is scattering in experimentally-obtained mechanical properties, reinforcing PBS matrix with long bamboo fibers is an effective method in concerning Young's modulus and tensile strength in the fiber direction.

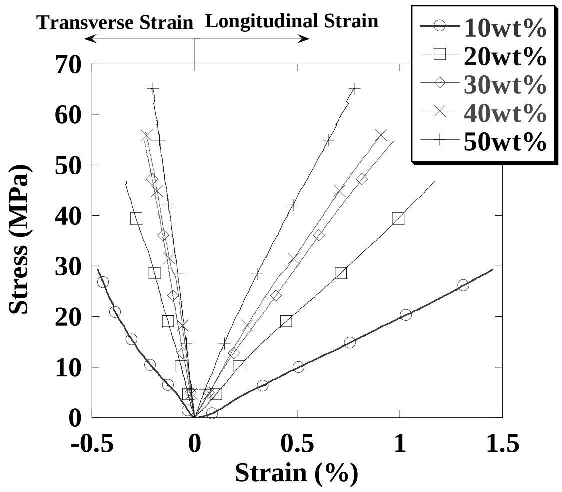


Fig.4 Stress-strain curves for BF/PBS in the fiber direction

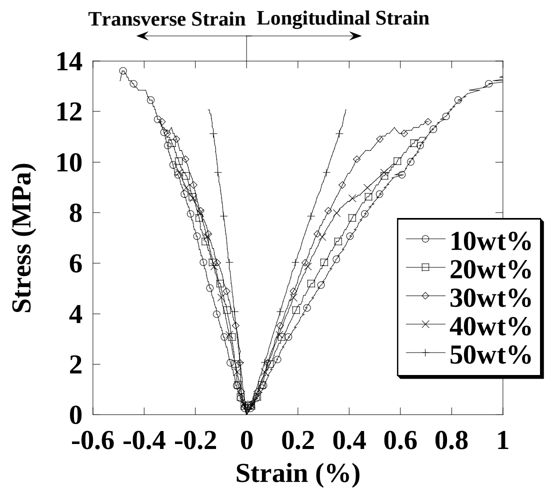


Fig.5 Stress-strain curves for BF/PBS in 45 degree direction

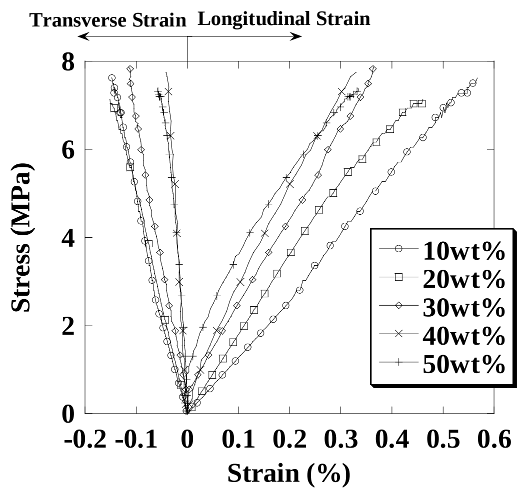


Fig.6 Stress-strain curves for BF/PBS in the transverse direction

3.3 Tensile test in 45 degree and the transverse direction

Figs.5 and 6 shows stress-strain curves for BF/PBS unidirectional composites in 45 degree and the transverse directions, respectively. Mechanical properties in 45 degree and transverse directions are listed in Table 3 and 4, respectively. Tensile strength in 45 degree direction is about 10MPa, and that in the transverse direction is about 6MPa. It is found that fiber weight fraction has a small effect on tensile strength. Young's modulus and the strain at fracture in 45 degree and the transverse directions show similar tendency with those in the fiber direction. Young's modulus is increasing with increasing with fiber weight fraction and the strain at fracture shows decreasing tendency.

3.4 Tensile test in BF/PBS cross-ply laminates

Fig.7 shows stress-strain curves for BF/PBS cross-ply laminate ($[0/90]_s$). Mechanical properties in BF/PBS cross-ply laminate are listed in Table 5. It is found that Young's modulus and tensile strength in BF/PBS laminate increases with increasing fiber weight fraction while the strain at fracture shows decreasing tendency. Experimentally-obtained tensile strength is seems to be valid because it is around half of tensile strength of unidirectional composite strength in the fiber direction.

Table 5 Mechanical properties in the cross-ply laminate

	Young's modulus (GPa)	Tensile strength (MPa)	Longitudinal strain at fracture (%)
10wt%	23.14	2.344	1.264
20wt%	34.41	4.199	1.051
30wt%	47.96	6.122	0.913
40wt%	53.79	7.406	0.876
50wt%	56.94	8.306	0.811

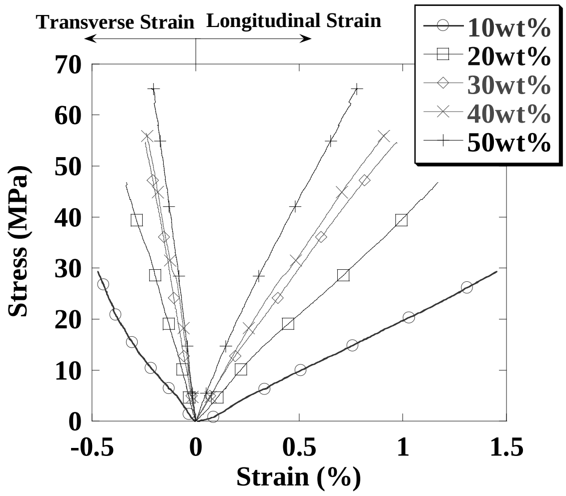


Fig.7 Stress-strain curves for cross-ply laminates

4. ANALYSIS

Based on the experimental results, Young's modulus and strength in unidirectional composites are discussed through the rules of mixture and Curtin's composite strength prediction analysis, respectively. Young's modulus and Poisson's ratio in BF/PBS cross-ply laminate are discussed through the laminate theory. We predicted the mechanical properties of unidirectional composites using fiber properties which are shown in Table 1. We predicted the mechanical properties in BF/PBS laminate using experimentally obtained composite properties which are listed in Table 2, 3 and 4.

4.1 Rules of mixture

The rules of mixture is known as a simple method in predicting of Young's modulus of composite materials. We assumed that fibers in composites are arranged in unidirectional and that fiber weight fraction is uniform throughout the composite. Rules of mixture do not consider Poisson's ratio. The composite longitudinal and transverse Young's modulus can be expressed as

$$E_L = E_f V_f + E_m (1 - V_f) \quad (2)$$

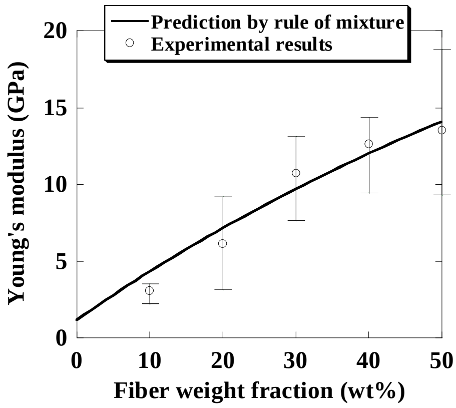
$$E_T = \frac{E_f E_m}{E_f V_m + E_m V_f} \quad (3)$$

Where E_L is Young's modulus in the fiber direction, E_T is Young's modulus in the transverse direction, E_f is fiber's Young's modulus, E_m is matrix Young's modulus, and V_f is fiber volume fraction.

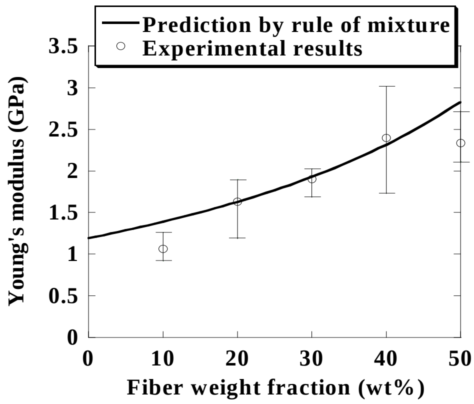
Fig.8 shows comparison between prediction by the rules of mixture and the experimental results in (a) the fiber direction and (b) the transverse direction. Although there is some discrepancy between the experimental results and analytical prediction, we believe Young's modulus in BF/PBS can be roughly predicted by the rule of mixture.

4.2 Curtin's composite strength prediction

Curtin proposed a analytical model which predicts composite strength in the fiber direction by considering the statistical nature of the fiber strength. Under the assumption that fiber break arise the other fibers supports the load equally, Curtin derived the composites strength and strain at fracture as[5]



(a) fiber direction



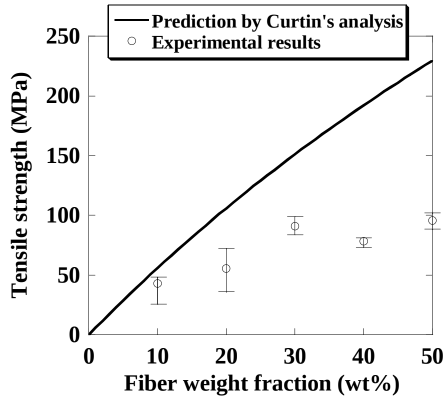
(b) fiber transverse direction

Fig.8 Young's modulus in BF/PBS. Comparison between prediction by rule of mixture and experimental results for (a) fiber direction and (b) transverse direction

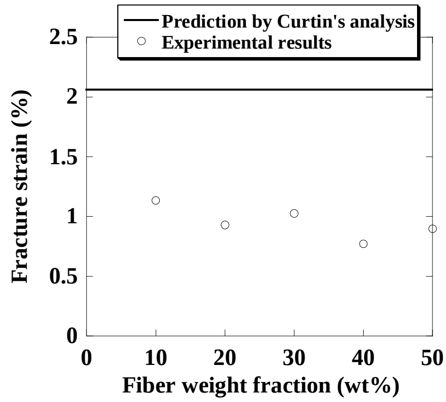
$$\sigma_{uts} = f\sigma_C\left(\frac{2}{m+2}\right)^{\frac{1}{m+1}}\left(\frac{m+1}{m+2}\right)+(1-f)\sigma_y \qquad (4)$$

$$\varepsilon_f = \frac{\sigma_c}{E_f}\left(\frac{2}{m+2}\right)^{\frac{1}{m+1}} \qquad (5)$$

where f is fiber volume fraction, σ_y is yield stress of matrix, and E_f is fiber Young's modulus. In addition, σ_c is fiber maximum stress in fibers fully fragmented. We use experimental results in Table 1 in prediction. Fig.9 shows comparison between prediction by Curtin's analysis and the experimental results for (a) tensile strength and (b) strain at fracture. The experimental results in composite strength and the strain at final fracture are lower than the analytical prediction. The discrepancy between the experimental results and the analytical prediction may be due to the assumption made in Curtin's model that assumes the equal load sharing. In other words, Curtin assumed that small effect of stress concentration in adjacent fibers to broken fibers by



(a) Tensile strength



(b) Strain at fracture

Fig.9 Comparison between prediction by Curtin's analysis and experimental results for (a) Tensile strength and (b) Strain at fracture

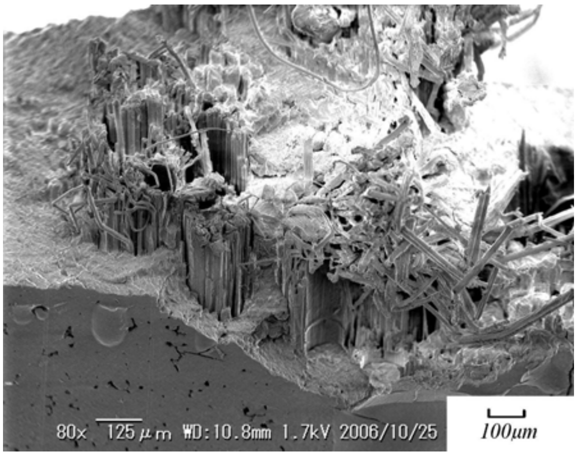


Fig.10 SEM image of BF/PBS (30wt%) fracture surface

debonding around break fiber. In this situation, there is fiber pull-out in fracture surface. Fig.10 shows SEM image of BF/PBS (30wt%) fracture surface. The fracture surface shows relatively flat appearance. This implies following failure mechanism. When one fiber break, it becomes starting point and fracture advances in plane, and causes the composite fracture. In this situation, the effect of stress concentration in adjacent fibers to break fibers should be considered.

4.3 Laminate theory

Young's modulus and Poisson's ratio in BF/PBS laminate are discussed through the laminate theory. In-plane stress resultant per unit width in a laminate is expressed by

$$\{N\} = [A]\{\varepsilon\}_x^0 + [B]\{\kappa\}_x \qquad (6)$$

where

$$[A] = \sum_{k=1}^{N} \left[\overline{Q}\right]^k (z_k - z_{k-1}) \quad ,$$

$$[B] = \frac{1}{2}\sum_{k=1}^{N} \left[\overline{Q}\right]^k \left(z_k{}^2 - z_{k-1}{}^2\right)$$

Assuming that there is no anti-plane deformation, the average stress can be expressed by

$$\{\overline{\sigma}\} = \frac{1}{2H}\{N\} = \frac{1}{2H}[A]\{\varepsilon\}_x^0 \qquad (7)$$

where 2H is the laminate thickness. The inverse relation is

$$\{\varepsilon\}_x^0 = \left[a^*\right]\{\overline{\sigma}\}, \quad \left[a^*\right] = 2H[A]^{-1} \qquad (8)$$

If we set the x direction the loading direction, Young's modulus and Poisson's ratio in x direction are

$$E_x = \frac{1}{a_{11}{}^*}, \quad \nu_{xy} = -\frac{a_{12}{}^*}{a_{11}{}^*} \qquad (9)$$

The matrix [A] of cross-ply laminates is expressed by

$$[A] = \sum_{k=1}^{N} \left[\overline{Q}\right]^k (z_k - z_{k-1}) = 2t\left\{\left[\overline{Q}\right]^0 + \left[\overline{Q}\right]^{90}\right\} \qquad (10)$$

where

$$\left[\overline{Q}\right]^0 = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}$$

$$\left[\overline{Q}\right]^{90} = \begin{bmatrix} Q_{22} & Q_{12} & 0 \\ Q_{12} & Q_{11} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix}$$

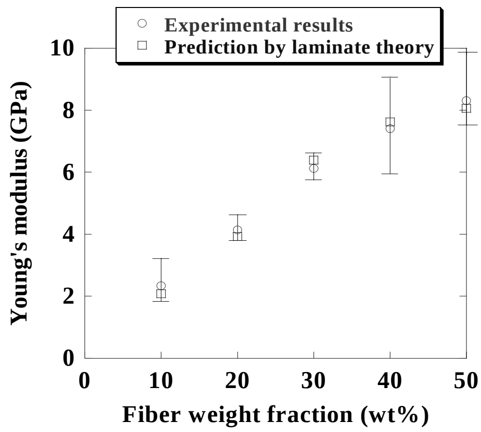
$$Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}}, \quad Q_{12} = \frac{\nu_{21}E_1}{1-\nu_{12}\nu_{21}},$$

$$Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}}, \quad Q_{66} = G_{12}, \quad \nu_{21} = \frac{E_2}{E_1}\nu_{12}$$

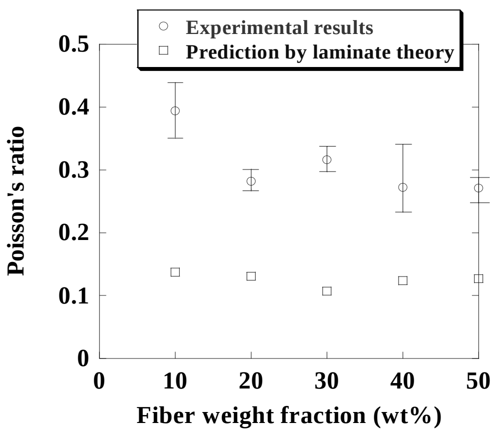
and [A] becomes

$$[A] = 2t\begin{bmatrix} Q_{11}+Q_{22} & 2Q_{12} & 0 \\ 2Q_{12} & Q_{11}+Q_{22} & 0 \\ 0 & 0 & 2Q_{66} \end{bmatrix} \qquad (11)$$

where E_1 is Young's modulus in fiber direction, E_2 is Young's modulus in transverse direction, $_{12}$ is Poisson's ratio and G_{12} is shear modulus, respectively. Using this equation, we predicted Young's modulus and Poisson's ratio in BF/PBS laminate. Fig.11 shows comparison between prediction by the laminate theory and experimental results for (a) Young's modulus and (b) Poisson's ratio. Prediction of Young's modulus in BF/PBS laminates shows good agreement with the experimental results. The discrepancy between experimental results and the analytical prediction of Poisson's ratio may be because that the reciprocal theorem is not valid in BF/PBS composites.



(a) Young's modulus



(b) Poisson's ratio

Fig.11 Comparison between prediction by laminate theory and experimental results for (a) Young's modulus and (b) Poisson's ratio

5. CONCLUSION

In the present study, we fabricated biodegradable unidirectional composite and cross-ply laminate which consist of bamboo fibers and PBS, and evaluated their mechanical properties.

(1) Young's modulus and tensile strength in unidirectional composite and cross-ply laminate increase with increasing fiber weight fraction but strain at fracture shows decreasing tendency.

(2) Young's modulus in unidirectional composites is predictable by the rules of mixture. Unidirectional composites tensile strength is lower than Curtin's prediction of strength which considers distribution of fiber strength.

(3) Young's modulus in BF/PBS cross-ply laminate is predictable by the laminate theory. However, analytical prediction of Poisson's ratio in BF/PBS cross-ply laminate is lower than the experimental results.

REFERENCE

1. H.Tsuji, Biodegradable polymers, Corona Publishing Co., Tokyo (2002), pp.1-15. (in Japanese)

2. K.Takura, Proceedings of the 30th Composites Symposium, Japan Society of Composite Materials (2001), pp.115-116.

3. Y.Kitamura, Proceedings of the 32th Composites Symposium, Japan Society of Composites Materials (2003), pp.29-30

4. K.Suzuki, Materials, 54 (2005), pp.887-894 (in Japanese)

5. G.Ben and T.Ishikawa, Advanced Composites Engineering, Baifukan (2005), pp.13-20. (in Japanese)