Tensile Properties of Natural Bamboo Fiber at Testing Temperature up to at 473K

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Abstract- We investigated the stress-strain curve and failure characteristics of natural bamboo fiber bundle which was taken by steam explosion treatment. Tensile test of the fiber was conducted at the temperature range from 293 to 473 K. Fracture morphology around o top of bamboo fiber tested at various temperatures was observed. It was found that failure behavior vary in testing temperature. It appreciated that the bamboo fiber exhibits a linear elastic response at all of tested temperature. Strength and elastic modulus obtained from various stress-strain curves decrease as temperature increases. It was predicted that failure morphologies at high temperature have an inclination to change gradually an unstable fracture state, owing to shape parameter, m, calculated by *Weibull* analysis and observation of fiber specimen after tensile test.

Keywords – Natural Bamboo Fiber, High Temperature test, Mechanical Properties, Fracture Behavior

I. Introduction

Composite materials are typically glass, carbon and aramid fiber-reinforced composites and widely use in various applications such as automobiles, trains, airplanes and sport goods. These show high mechanical and thermal properties. However, these advantages cause environmental problems in disposal by incineration and pulverization. In order to overcome environmental problems, development of environmentally friendly composites is required in recent years [1]. Natural fiber has superior environmental performances as recyclability and lower pollutant emission [2]. The use of natural fiber as reinforcements in polymer matrix composites to replace synthetic fiber is receiving increasing attention. On the other hand, natural fiber has with poor wet-ability and absorb-ability resulting from the hydrophilic property of plants. To improve the interfacial bonding strength in polymer matrix, either surface modification of the fiber with alkali treatment [3] or plasticization of the fibers [4] can be carried out.

Bamboo is a renewable resource and uses in many parts of the field, and has high strength, flexibility and rapid growth [5]. For example, it can grow to height of one meter within one week in moderate weather condition. Researches [6-8] on bamboo fiber reinforced polymer matrix are shown, and mechanical properties, composite forming and modified fiber surface by some chemical or other treatments were written. For products of composites including polypropylene, polyethylene and biodegradable resin with thermal-process, it is important to evaluate mechanical properties at approximately temperature of 433 to 463 K (160 to 190 °C)

The aim of present study is to investigate tensile deformation response and mechanical properties at elevated temperatures, and to discuss on failure mechanism at various temperatures.

II. Experimental Procedure

A. Bamboo fiber –

Bamboo was purchased from BAN Corp. (Tokushima pref., JAPAN). Bamboo fiber bundle was obtained from steam explosion method as shown conditions in Table 1. Fiber with diameter around 200 μm and length of 50 mm were taken. The xylem (soft-wall cell) on the fiber was removed by moist cotton paper, and then fiber was dried ranging at 313 K (40 °C) to 323 K (50 °C) for 24 hours into heater. The bamboo fiber after dry treatment has water content of 4.41%, as a result of moisture meter (MX-50, A&D Co.) experiment.

Diameter and cross-section area of the bamboo fiber were determined by Tanabe's method according to reference [9].

Table -1 Conditions of the steam explosion treatment an one process

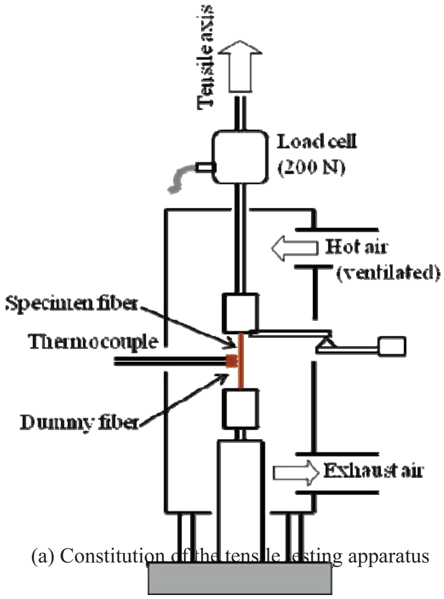
Order	Time (ksec.)	Temperature (K)	Pressure (MPa)	Number of explosions an one process
1	0.06	443	0.7	1
2	2.4	449	0.7	1
3	0.18	443	0.7	6

B. Tensile test –

Tensile test in accordance with JIS R7606 standards (Carbon fibre – Determination of the tensile properties of the single – filament specimens) was carried out at several temperatures of range from room temperature (293K, 20 °C) to 473K (200 °C) using tensile testing machine of lab' own work with an initial loading speed of approximately 1.0 mm/min for specimen that was prepared in gage length of 50 mm. Figure 1 is tensile testing machine (LSC-1/30, Tokyo Testing Machine INC.) used with heating furnace in present study. The system consists of the tensile testing apparatus aided with a personal computer containing "EXCEL software". In this system, tensile load is measured by one load cell (TCLZ-200NA, Tokyo Sokki Kenkyujo Corp.) with capacity of 200 N, and displacement is measured by cantilever type extensometer (CE-10, Tokyo Sokki Kenkyujo Corp.) in pursuit on loading axis to movement. Load and displacement data are conducted and stored in digital storage oscilloscope, then transferred from the oscilloscope to the personal computer by a USB (Ver.2.0) interface. The elastic modulus, tensile strength and failure strain were calculated from the stress-strain curve. Tenth specimens are prepared at each testing temperature.

C. Fracture Behavior Observation –

To observation failure morphologies around the top of bamboo fiber after tensile tests at elevated temperatures, digital microscope (KEYENCE, VHX-2000) was used.



(a) Constitution of the tensile testing apparatus

(b) Photograph showing tensile testing machine

Figure 1. Tensile testing apparatus of the bamboo fiber at elevated temperature range from 303 to 473 K

III. Experiment and Result

A. *Mechanical properties –*

Figure 2 shows typical stress-strain curves of the bamboo fiber at different testing temperatures. R.T. in this figure means room temperature. It appreciated that the bamboo fiber exhibits a linear elastic material at all of testing temperature. These maximum strength and failure strain values obtained from various stress-strain curves decrease as temperature increases. It is important to fabricate bamboo reinforced composite at T = 453 K (180 °C) and 473 K (200 °C). It is indicates that the bamboo fiber to applied load during the thermal-pressing at high temperature are broken. Figure 3 (a) shows change of the tensile strength of the bamboo fiber obtained from tensile test with different testing temperatures. Strength is decreasing with increasing temperature, and maximum tensile strength is at room temperature, which can be expressed by following equation ($R = 0.992$):

$$\sigma_B = -3.316 \cdot T + 1684 \qquad (1)$$

Where, σ_B is tensile strength of the bamboo fiber at elevated temperatures and T means testing temperature in degrees Kelvin. If $\sigma_B=0$ assign to an equation (1), the temperature becomes approximately 508 K (235 °C) (Adopted extrapolation). This indicates temperature when thermal-decomposition reaction of cellulose molecule is started at range between from 473 K (200 °C) to 543 K (270 °C) in reference [10]. According to study on effect of the heating temperature on the strength of bamboo fiber by authors [11,12] and *Takagi and Mori* [13], they were reported that the strength of the bamboo fiber began to decreasing at temperature range from 403 K (130 °C) to 413 K (140 °C) as shown in reference [11,12]. This temperature domain is lower than temperature to flow polymer matrix in composite and to heat bamboo in steam explosion treatment as Table 1.

Figure 3 (b) shows change of the elastic modulus of the bamboo fiber obtained from tensile test with different temperatures. These elastic modulus values decrease as temperature increases, and maximum elastic modulus value is obtained at room temperature. The temperature dependence of elastic modulus was the same as that of tensile strength. On the other hand, according to *Takagi and Mori* [13], it was reported that elastic modulus of the bamboo fiber after heat treatment has no change. Therefore, the valuable suggestion is given for the recovery phenomena of elasticity of bamboo fiber.

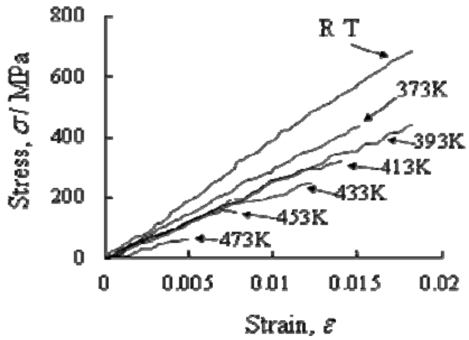
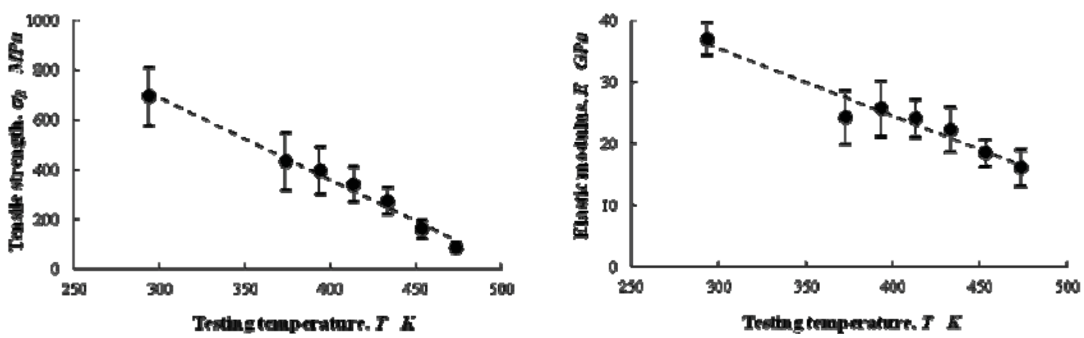


Figure 2. Typical stress-strain curves of the bamboo fiber at various testing temperatures



(a) Tensile strength, σ_B against testing temperature, T

(b) Elastic modulus, E against testing temperature, T

Figure 3. Change of the tensile strength, (a) and elastic mudulus, (b) for bamboo fiber at various testing temperatures

B. Weibull Statistics –

The classical theory of the statistical strength of brittle materials was known as *Weibull* analysis. The strength of the fiber obeys the single *Weibull* cumulative distribution function, *i.e.*

$$F(x)=1-exp(-(x/\eta)^m) \qquad (2)$$

Where $F(x)$ is the failure probability of the bamboo fibers under an applied stress no greater than x, η and m are the scale and shape parameters of *Weibull* distribution, respectively. $F(x)$ was given from median rank method.

Figure 4 shows the *Weibull* plots of the tensile strength at different testing temperatures. The *Weibull* shape parameter, m, which means variance of strength [14], were 4.38 and 5.05 at room temperature and 473 K (200 °C), respectively. Thus, in strength at room temperature, the width of the variance is winder than that at 473 K.

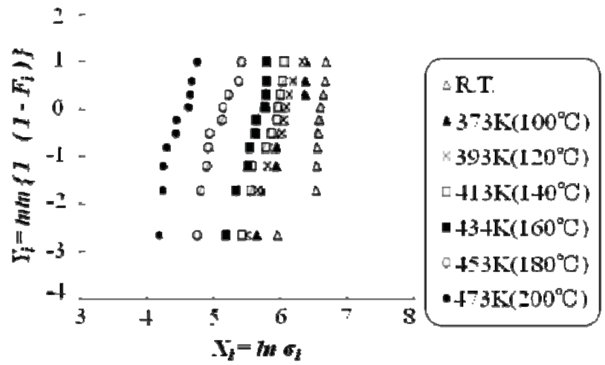
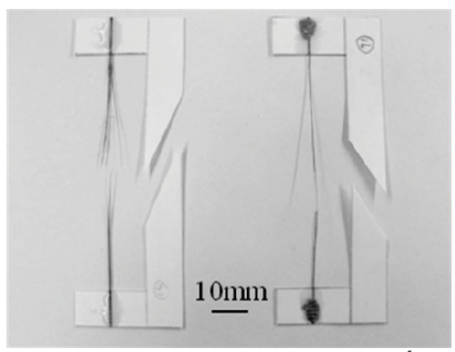


Figure 4. Change of the tensile strength for bamboo fiber at various testing temperatures

C. Failure Morphologies at Elevated Temperatures –

Failure morphologies were found to vary with temperature. Figure 5 (a) and (b) present macroscopic fractured fiber tested at room temperature and 473 K (200 °C), respectively. Vertical direction shows a tensile axis in Figure 5. At room temperature, it was observed splitting fracture in whole specimen, and at 473 K, however, fracture point was localized. As temperature increasing, the overall failure morphologies of the specimens showed the tendency to exhibit in brittleness. It was predicted that failure morphologies at high temperatures have an inclination to change gradually an unstable fracture state, resulting from observation of specimen tested.



(a) Room temperature (b) 473 K (200℃)

Figure 5. Macroscopic failure morphologies of the bamboo fiber tested at room temperature and 473 K, respectively

Figure 6 (a) to (g) present microscopic observation at the tip of fiber tested at room temperature to 473 K (200 °C). The fracture at different testing temperatures undergoes a ductile to brittle transition. At room temperature, the fiber monofilaments fail at a random location along the gage length of the tensile testing specimen. The result is that a large number of microcrack form prior to final failure at room temperature. However, fiber failure morphologies at high temperature as shown in Fig.6 (g) indicate the largest suitably oriented crack propagates unstably when the critical stress intensity was attained.

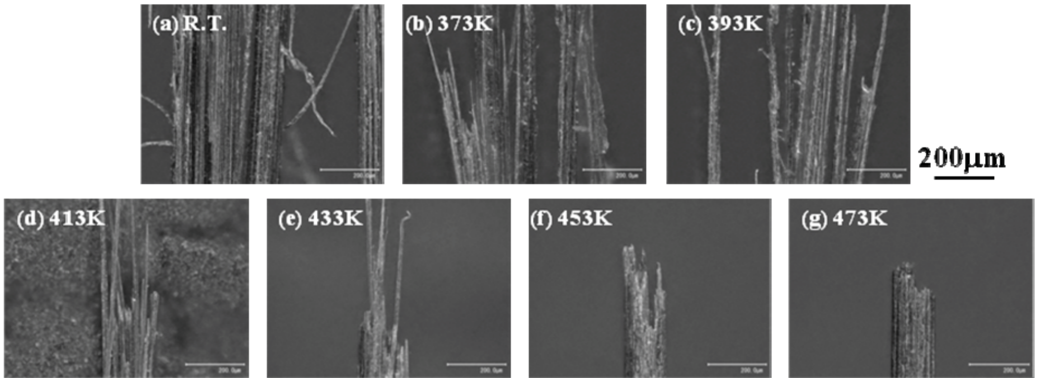


Figure 6. Microscopic observation at the tip of bamboo fiber tested at room temperature and 473 K, respectively

D. Possibility as a reinforcing material of Bamboo fiber –

The result of this investigation reveals that tensile strength and elastic modulus of a bamboo fiber is dependent on temperature range from room temperature to 473 K. Temperature dependences of strength and elastic parameter in reinforcing material is important to design composite products with thermal-process. E-glass fiber [15] has tensile strength, $\sigma_B = 2000\ MPa$ or more, elastic modulus, $E = 72\ GPa$ and density, $\rho = 2.6\ Mg/m^3$ in general. Thus, specific modulus, E/ρ and specific strength, σ_B/ρ of E-glass are $26.7\ GPa/Mg/m^3$ and $769\ MPa/Mg/m^3$, respectively. On the other hand, those of bamboo fiber are $E/\rho = 46.3$ and $\sigma_B/\rho = 861$ at room temperature. It was used as $\rho = 0.8\ Mg/m^3$ of bamboo fiber [16]. Therefore, in view of material selection, bamboo fiber reinforced plastic composites could be expected for lightweight products.

IV.CONCLUSION

Tensile deformation response and mechanical properties at elevated temperatures of the natural bamboo fiber were investigated, and discussed on failure morphologies at high temperature based on *Weibull* analysis.

The results are as follows.

(1) It appreciated that the bamboo fiber exhibits a linear elastic material at all of testing temperature, resulting from stress-strain curves of the bamboo fiber tested.

(2) Tensile strength of the bamboo fiber is decreasing with increasing temperature, and maximum tensile strength is at room temperature, which can be expressed as:

$$\sigma_B = -3.316 \cdot T + 1684$$

(3) The temperature dependence of elastic modulus was the same as that of tensile strength at elevated temperatures.

(4) At room temperature, it was observed splitting fracture in a whole specimen, and at 473 K, however, fracture point was localized. As temperature increasing, the overall failure morphologies of the specimens showed the tendency to exhibit in brittleness.

(5) In view of material selection based on specific modulus, E/ρ and specific strength, σ_B/ρ, bamboo fiber could be expected for reinforcing fiber of composite material.

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