Construction and Building Materials 93 (2015) 558–563

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Mechanical properties and extended creep behavior of bamboo fiber reinforced recycled poly(lactic acid) composites using the time–temperature superposition principle

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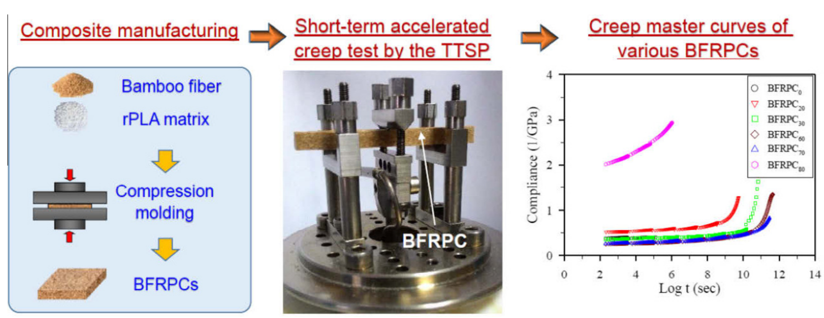
HIGHLIGHTS

- Mechanical and creep properties of BFRPCs with various fiber loadings were studied.
- BFRPC with 60 wt% fiber exhibited the best flexural properties and creep resistance.
- The E' of BFRPCs above the T_g of rPLA increased with increasing fiber loading up to 60 wt%.
- Nearly perfect superposition of master curves was obtained using the TTSP method.
- The modulus of all BFRPCs reduced in the range of 27–40% over a 30-year period.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 February 2015
Received in revised form 15 June 2015
Accepted 16 June 2015

Keywords:
Bamboo fiber
Creep behavior
Mechanical property
Poly(lactic acid)
Time–temperature superposition principle

ABSTRACT

The present study investigates mechanical properties and creep resistance of bamboo fiber reinforced recycled PLA composites (BFRPCs). The results revealed that the modulus of rupture and modulus of elasticity of BFRPCs increased with increasing bamboo fiber loading up to 60 wt% and then declined sharply as the fiber increased further. Short-term accelerated creep tests on BFRPCs were conducted at a series of elevated temperatures by time–temperature superposition principle. As a result, the BFRPC with 60 wt% fiber exhibited the best creep resistance among all the BFRPCs, and then decreased when the fiber loading was more than 70 wt%.

1. Introduction

In recent years, the depletion of fossil fuels and the growth of environmental awareness have motivated many researchers to develop bio-materials. Consequently, natural fiber biocomposites, such as wood plastic composites (WPCs), have become important in composite science. WPCs are of great interest in construction applications due to their advantages, including dimensional stability, moisture resistance, mechanical properties, and durability [1–4]. However, one of their disadvantages is the change in WPC mechanical properties with temperature, leading to limits in wider applications. Therefore, it is also important to investigate the temperature sensitivity of WPC properties, such as creep behavior, because WPCs exhibit a strong time–temperature dependent response. On the other hand, it is time-consuming and

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http://dx.doi.org/10.1016/j.conbuildmat.2015.06.038

expensive to conduct full-scale creep tests in a normal time scale. In this study, an accelerated creep test based on the time–temperature superposition principle (TTSP) was implemented to predict the long-term creep response. Methods using this principle have been employed to confirm that TTSP is applicable to various WPCs [5–8].

Among bio-based polymers, poly(lactic acid) (PLA), which is made from renewable raw agricultural materials, is a versatile biodegradable polymer used in many applications. PLA has great potential to replace petroleum-based plastics due to its high stiffness and strength compared with polystyrene. However, the drawbacks of PLA include its brittleness, low thermal resistance, and slow crystallization rate, which limit wider applications. To overcome these drawbacks and reduce fossil fuel consumption, natural fiber reinforced PLA has been studied to improve the characteristics of PLA and obtain fully bio-based composites [9–11]. Compared with inorganic fillers, natural fibers such as wood, bamboo, flax, ramie, jute, kenaf, and hemp have numerous advantages: low cost, low density, high toughness, good specific strength properties, renewability, and biodegradability [9,12–15]. In particular, bamboo fiber reinforcement has great potential to improve the thermal and mechanical properties of PLA composites due to its excellent physical properties [16–19]. Additionally, bamboo fiber is easily obtained because of its wide distribution across Asia [20] and fast growth rate in comparison with other plants having fibers [21–23]. Furthermore, bamboo fiber reinforced PLA composites (BFRPCs) would utilize large amounts of bamboo shavings and sawdust, by-products of the bamboo-processing industry. To date, investigations into BFRPCs focused primarily on the effects of various attributes on the thermal and mechanical properties of the composites, such as fiber type, fiber loading, functional additives, and fiber modification to increase the compatibility between the hydrophilic natural fiber and hydrophobic polymeric matrix [24–26]. However, there is little information available on detailed investigations of dynamic mechanical properties and creep behavior of BFRPCs. Therefore, in addition to qualifying their dynamic mechanical properties and static flexural properties, the main objective of the present study was to investigate the time–temperature dependent response and extended creep behavior of BFRPCs using TTSP.

2. Materials and methods

2.1. Preparation of bamboo fibers and recycled poly(lactic acid)

Dried shavings from 3-year-old kei-chiku bamboo (makino bamboo; *Phyllostachys makinoi* Hayata) were provided by the local bamboo-processing factory. Bamboo fibers were prepared by hammer-milling and sieving and fibers between 30 and 60 mesh were investigated. A recycled PLA (rPLA) was purchased from Orbit Polymers Co., Ltd. (Taichung, Taiwan) and had a melting temperature of 145–155 °C.

2.2. Composite panel manufacture

Manufacturing BFRPCs: the flat platen pressing process was applied in our previous papers [2,27]. The weight ratios of the oven-dried bamboo fibers (moisture content <3%) to rPLA powder were 5/95, 10/90, 20/80, 30/70, 40/60, 50/50, 60/40, 70/30, and 80/20 (wt%). The density of the BFRPCs was 1200 ± 30 kg/m^3. The dimensions of the BFRPC samples were 300 mm × 200 mm with a thickness of 4 mm. All BFRPCs were produced in a two-step pressing process as follows: (1) hot pressing (2.9 MPa) at 175 °C for 3 min; and (2) finishing by cold pressing until the temperature of BFRPCs decreased to 30 °C.

2.3. Flexural properties

The modulus of rupture (MOR) and modulus of elasticity (MOE) of the samples were determined by a three-point static bending test with a loading speed of 1.7 mm/min and with a span of 64 mm (ASTM D790-07). The dimensions of the sample were 80 mm × 16 mm with a thickness of 4 mm. Five samples of rPLA composites with various fiber loading were tested at 20 °C. The samples were conditioned at 20 °C and 65% relative humidity for a week before testing.

2.4. Dynamic mechanical analysis (DMA) and short-term accelerated creep test

The dynamic mechanical properties of the BFRPCs were measured in single cantilever bending mode (DMA 8000, PerkinElmer) at a heating rate of 2 °C/min and a frequency of 1 Hz. The storage modulus (E') and loss tangent (tan δ) were recorded in the range of 25–160 °C. The dimensions of the sample were 30 mm × 10 mm with a thickness of 4 mm. Additionally, according to TTSP, a dynamic mechanical analysis (DMA) was carried out to determine the glass transition temperature (T_g) and active energy (E_a). These experiments were conducted in dual cantilever mode under isochronal conditions at frequencies of 4, 8, 12, 16, 20, 24, 28, and 32 Hz. The dimensions of the sample were 50 mm × 10 mm with a thickness of 4 mm. Tests were conducted in the range of 25–120 °C at a scanning rate of 1 °C/min.

TTSP, using a real-time short-term creep response at elevated temperatures, is used to predict the long-term creep performance of the composites. The creep compliance is given by $S(T_{ref}, t) = S(T_{elev}, t/\alpha_T)$, where S is the creep compliance as a function of temperature and time, T_{ref} is the reference temperature, T_{elev} is the elevated temperature, and α_T is the shift factor. The master curve of creep compliance and the activation energy of the glass transition relaxation were also determined by DMA. Creep and creep recovery cycles were conducted at isotherms between 20 and 50 °C in intervals of 5 °C. A three-point bending mode with a span of 40 mm was used. For each isotherm, 30% of the average flexural strength was applied for 1 h, followed by a 1 h recovery period.

2.5. Static analysis

All results are expressed as the mean ± SD. The statistical analysis was performed with one-way ANOVA and Scheffe's post hoc test. The results with $P < 0.05$ were considered to be statistically significant.

3. Results and discussion

3.1. Density, moisture content, and static flexural properties of the samples

The density, moisture content, and flexural properties of the BFRPCs are summarized in Table 1. In general, density and moisture content may directly affect the flexural properties of a polymer composite. Except for the density of BFRPC$_{80}$ (∼999 kg/m^3), there was no statistical significance ($P > 0.05$) in density among all composites (∼1200 kg/m^3). The decrease in the density of BFRPC$_{80}$ is attributed to the observable thickness swelling that occurred after compression molding. It can be seen that moisture content increased with increasing fiber loading. With the addition of 80 wt% fiber to PLA, the moisture content increased significantly from 0.4% (BFRPC$_0$) to 3.9% ($P < 0.05$). As expected, the addition of more fiber to a matrix leads to higher moisture content because