Comparison of Bending Creep Behavior of Bamboo-based Composites Manufactured by Two Types of Stacking Sequences

Xinxin Ma, Ge Wang, Zehui Jiang,* Yu Xian, and Haidong Li

The study of viscoelastic and mechano-sorptive creep on bamboo laminated veneer lumber (BLVL) and bamboo/poplar plywood (BPP) is described in this paper. Bending creep tests parallel to the grain were carried out on two bamboo-based composites for a length of 90 days. The specimens measured 500 mm × 20 mm × 12 mm. Based on the experimental data, the creep curves of two boards were evaluated. The results are summarized as follows: (1) the anti-creep property of BLVL was better than that of BPP; (2) two creep curves were successfully approximated using the Burgers model and the power law model. The required experimental term for the creep test to estimate an accurate long-term curve is 2 or 3 years when the power law is used for the estimation; and (3) compared with the creep curve in a constant environment, the creep deformation changed more dramatically under varying environment.

Keywords: Bamboo-based composite; Creep; Mechano-sorptive creep; Burgers model; Power law

Contact information: International Center for Bamboo and Rattan, Beijing, China, 100102;
** Corresponding author: mahanyum@163.com*

INTRODUCTION

Bamboo-based composites are used in many fields, including the construction of large-scale buildings. As a new type of constructional material, it is very important to study its resistance to creep because creep in wooden structures can lead to serviceability problems due to excessive deformation or strength loss. The creep behavior of wood and wood-based composites has been widely observed (Armstrong 1972; Bodig and Jayne 1982; Ranta-Maunus 1990; Fridley and Tang 1992). Creep, especially mechano-sorptive creep, is very important for obtaining information about the long-term performance characteristics of wood and bamboo structures under ambient conditions.

Viscoelastic creep is defined as creep strain that is primarily dependent on time. The creep rate is dependent on other factors, such as stress, stress history, temperature, and moisture content. In measurements, the stress, temperature, and moisture content are normally held constant (Hanhijarvi and Hunt 1998). Mechano-sorptive creep, on the other hand, is defined as creep strain that is primarily dependent on change of humidity, either increasing or decreasing. It causes wood to creep more than at constant humidity, the strain depending only on the amount of moisture change, not on the time of the rate of change (Armstrong and Kingston 1962; Grossmann 1976).

Many methods have been investigated to improve tensile and flexural creep behavior of bamboo fiber and bamboo fiber-reinforced composites (Jain *et al.* 1992; Yu and Jiang 2011; Abdul Khalil *et al.* 2012). In order to study the long-term efficiency of bamboo laminas reinforcing low-quality precocious wood beams, creep behavior and the influence of the bamboo reinforcement was discussed (Amino 2005). However, the topic of bamboo creep behavior has not been fully investigated. Regarding the utilization of bamboo-based composites, the study on the time-dependent behavior is indispensable.

This study is limited to two bamboo-based composites. They were subjected to one level of mechanical load under both uncontrolled and controlled environmental conditions. The influence of these factors on the viscoelastic and mechano-sorptive properties of wood were analyzed using the experimental data.

EXPERIMENTAL

Materials

The experimental program included tests done under uncontrolled environmental conditions on bamboo laminated veneer lumber (BLVL) and bamboo/poplar (5/4) plywood (BPP). Three-year old Cizhu bamboo (*Neosinocalamus affinis*) was obtained from Yibin, Sichuan Province, China. An untwining machine was used for brooming and rolling the bamboo strips into a laminated sheet. These bamboo bundle sheets and poplar veneers were finally consolidated into two types of board by hot pressing. The ply organization for BBP sheets was aligned in the length direction with cross-laminated bamboo bundle and poplar veneer, while the layers of bamboo bundle sheet for BLVL were laid in parallel. The sampling was carried out according to the standard ASTM D6815-09 (span to depth ratios range between 17 an 21). Each board was sawn into two specimens with dimensions of 500 mm × 20 mm × 12 mm. Figure 1 shows the comparison of cross-sections for BLVL and BPP. Average wood density, bending modulus of rupture (MOR), and modulus of elasticity (MOE) of all specimens were measured (Table 1).

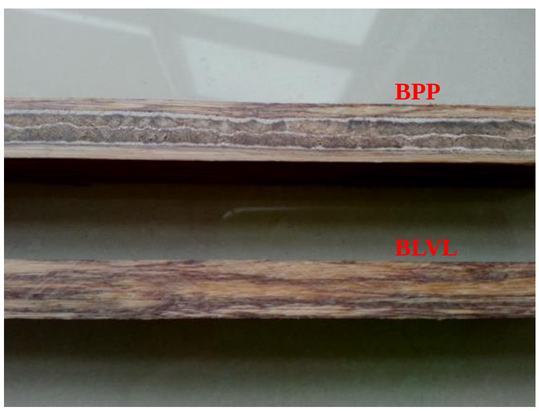


Fig. 1. Cross-sections of BPP and BLVL

Table 1. Physico-Mechanical Properties of Loaded Specimens

Material type	Density (g/cm^3)	MOR (MPa)	MOE (GPa)	Load(kg)
BPP	0.99	124.3	13.77	25.1
BLVL	1.03	140.7	15.51	25.6

Methods

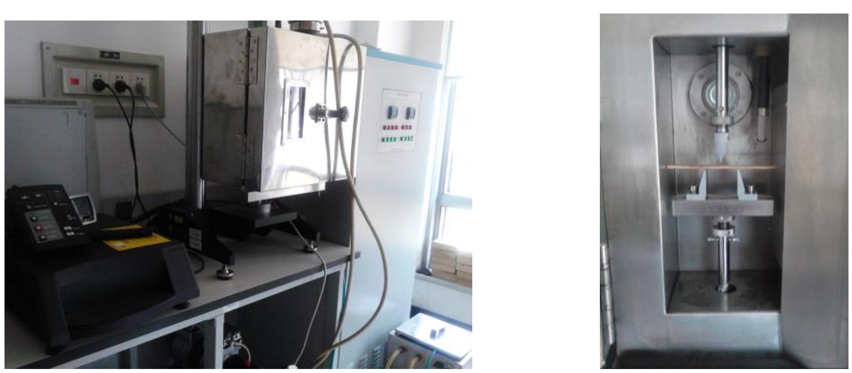
Bending creep tests in an uncontrolled environment

Bending creep tests were carried out for 90 days (May 31, 2013 to August 30, 2013) under three-point loading conditions with span lengths of 300 mm (Chen and Lin 1997). The load corresponded to 30% of the short-term ultimate limit state load. The deflection was measured by a dial gauge (accuracy of measurement, 0.01 mm; Taiwan Eee) set at the center of the specimens. Figure 2 shows the bending creep fixture for applying long-term loads to two specimens. Temperature and humidity were measured by a Hygromaster meter (KeJian HTC-1, China). For approximately 90 days, four test specimens were subjected to sustained loads in an uncontrolled environment (the basement of the International Center for Bamboo and Rattan).

Fig. 2. Long term creep fixture used in the bending creep tests of specimens

Mechano-sorptive creep tests in a controlled environment

Three specimens of each group were used for tests in a controlled environment, with dimensions of 90 mm × 11 mm × 2 mm. The short-term creep test was carried out in a chamber in which both temperature and humidity were controlled. Deflection was measured using the video-extensometer of an MTS machine (Instron 5848; USA) that was connected to the chamber (Fig. 3). The bending loads were nearly 15% of the short-term ultimate limit state load. Because of the nearly linear response at low levels of stress, Boltzmann's superposition principle applies to stress-strain behavior for stresses up to 40% of the short-term strength (Holzer *et al.* 1989).



a b

Fig. 3. Mechano-sorptive creep instrument of specimens

Mechano-sorptive creep tests were carried out at a temperature of 25 °C. The relative humidity was varied from 65% to 85%. The cycle length was six hours. Four moisture change cycles were performed for each creep test (Pu and Tang 1997).

RESULTS AND DISCUSSION

Evaluation of Creep Deformation by the Burgers Model

Figure 4 presents the temperature and humidity under uncontrolled environmental conditions. The creep behavior of bamboo laminated veneer lumber and bamboo/poplar plywood is shown in Table 2.

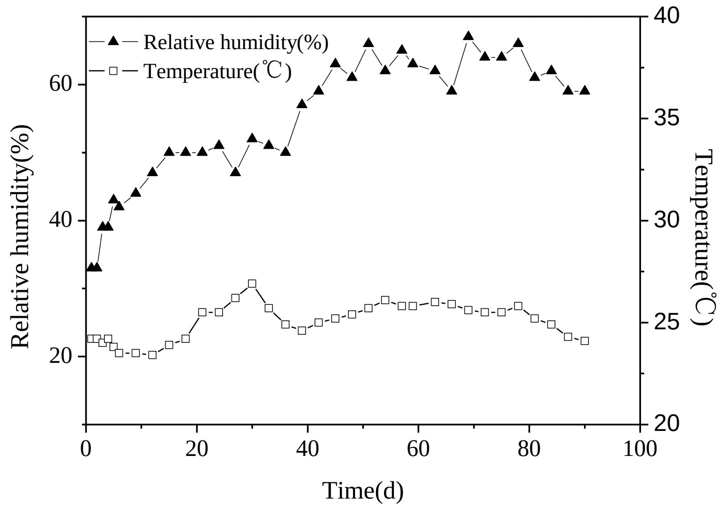


Fig. 4. Environmental conditions in the uncontrolled environment

Table 2. Creep Behavior of Bamboo-based Boards

Material type	Initial deflection (mm)	Final deflection (mm)	Relative creep after 1 s $\phi(t_0)$	Relative creep after 90 days $\phi(t_{90})$
BLVL1	2.86	3.61	0.0032	0.26
BLVL2	2.88	3.93	0.0030	0.36
Mean value	2.87	3.77	0.0031	0.31
BPP1	2.93	4.27	0.0034	0.46
BPP2	2.94	4.59	0.0034	0.56
Mean value	2.935	4.43	0.0034	0.51

The relative creep ($\phi(t)$) was defined as:

$$\phi(t) = \frac{\eta(t)}{\eta_0} - 1 \tag{1}$$

in which η_0 and $\eta(t)$ signify the initial deflection and the deflection of the board, respectively, after t days from loading.

It is shown in Table 2 that the relative creep of BLVL was lower than that of BPP. The mean values for relative creep of BLVL ranged between 0.0031 and 0.31 under experimental ranges, whilst the relative creep of BPP was from 0.0034 to 0.51.

Several models have been developed to describe the primary and secondary creep response of wood under a combination of load histories and hygrothermal conditions (Dinwoodie *et al.* 1991; Bengtsson 2000). To evaluate the time-dependent response of bamboo composites based on the test data, identification of a reliable creep model is necessary. The Burgers model and the power law are frequently used. The Burgers model is composed of Hookean springs and Newtonian dashpots in parallel or in serial combinations to provide an analogous system equivalent to the physical creep behavior of the material (Bodig and Jayne 1982). When a constant stress is applied, the total strain $Y(t)$ at time t is the sum of strains in the three constitutive units. It works well over limited time domains. The power law, widely used in the polymer field, has some predictive capability.

The Burgers model, also known as the 4-element model, works well at a constant temperature (Pierce *et al.* 1979),

$$Y(t)=\frac{\sigma}{E_1}+\frac{\sigma}{E_2}[1-\exp(\frac{-tE_2}{\eta_2})]+\frac{\sigma}{\eta_3}t \tag{2}$$

which may be rewritten as,

$$Y(t)=\beta_1+\beta_2[1-\exp(-\beta_3 t)]+\beta_4 t \tag{3}$$

where $\beta_1 = \sigma/E_1$, $\beta_2 = \sigma/E_2$, $\beta_3 = E_2/\eta_2$, and $\beta_4 = \sigma/\eta_3$ are unknown parameters to be estimated. β_1 represents initial elastic deformation and is associated with the spring constant E_1; β_2 and β_3 represent the delayed elastic or recoverable creep component and are associated with the combined effects of the spring constant E_2 and the dashpot damping coefficient η_2 ; and β_4 represents the flow component or irrecoverable creep.

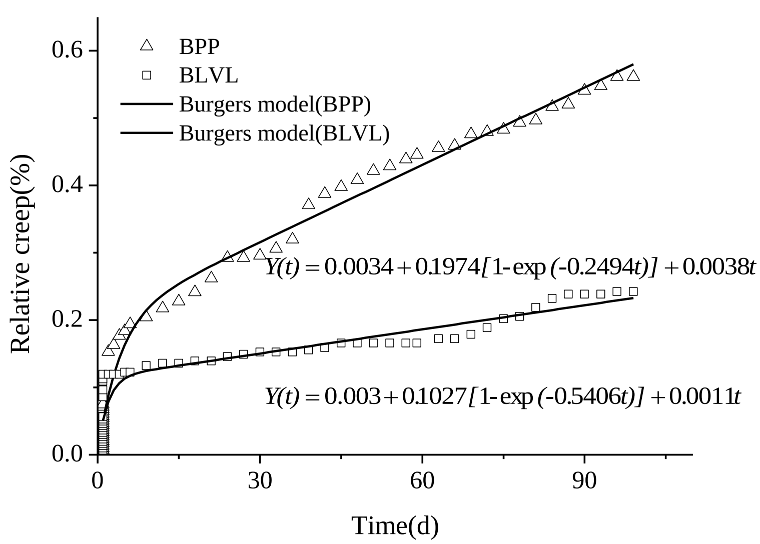


Fig. 5. Relative creep and Burgers model response curves fitted to creep data

A computer program (OriginPro 8.0, American OriginLab Corporation) was written to estimate the parameters of the 4-element models and to produce a plot of the two creep curves superimposed on the original data. Four parameters of β_1, β_2, β_3, and β_4 in Eq. 3 were evaluated according to the characteristic of the curve. The estimated parameters are shown in Table 3, and the graphical representation is shown in Fig. 5. There are a number of points that emerged from the curve-fitting and plotting exercise: (1) The multiple correlation values were good for the two boards, but BPP provided the better overall fit to the data. This is an important consideration when predicting future behavior; (2) The 4-element estimated parameters, β_1, of all specimens were somewhat different from the true initial deflection. The values of β_1, representing the elastic behavior of the two boards, could be used to find an estimate of MOE. β_1 of BLVL was found to be smaller than that of BPP, which means the elastic deformation of BPP was larger than that of BLVL. It showed that BPP is more susceptible than BLVL to elastic deformation; (3) The creep rates of two specimens in each group were different, though the initial deflections of each specimen were similar. This phenomenon could be related to the different viscoelastic properties of the two boards; and (4) with the same creep time, the less the value of β_4, the smaller the irrecoverable creep deflection. It can be seen in Table 3 that the value of β_4 for BLVL was smaller than that for BPP. This indicates that the irrecoverable creep deflection of BLVL was lower than that of BPP (Pierce and Dinwoodie 1977).

Table 3. Creep Coefficients of Burgers Model

Material type	Estimated parameter				Correlation coefficient
	β_1	β_2	β_3	β_4	R^2
BPP	0.0034	0.1974	0.2494	0.0038	0.9853
BLVL	0.0030	0.1027	0.5406	0.0011	0.9755

Estimation by Power Law

The design values of relative creep after 50 years are usually calculated with the power law model, adopted in the Standard for Structural Design of Timber Structures issued by the Architectural Institute of Japan (2006) (Aratake *et al.* 2011). Then the power law was chosen to estimate the creep curve in this study. Figure 6 shows comparisons between actual creep deflections and creep deflections calculated by applying the power law [$\delta_c(t)$],

$$\delta_c(t) = At^N \tag{4}$$

where the constants A and N, which are called the creep constant and deceleration exponential.

According to correlation coefficient, the power law model does not fit the creep data very well as the Burgers model. The fluctuation of the creep deflections resulting from changes in temperature and humidity were not evident when calculated using the power law, so taking atmospheric conditions into consideration may not be practical for predicting creep curves.

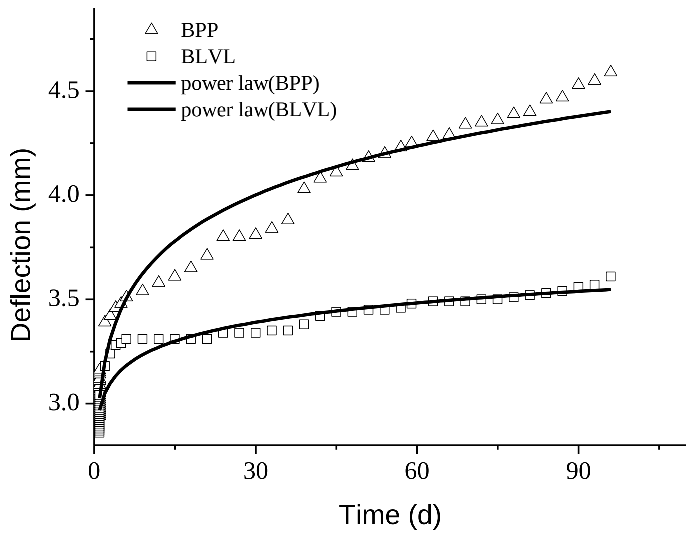


Fig. 6. The actual creep deflections and creep deflections calculated using the power law

On the basis of power law (Eq. 4), the relative creep after 50 years (δ_{50}/δ_0) was examined. The δ_{50}/δ_0 values were calculated by the following equation, with constants estimated from data covering several time points (1, 15, and 45 days):

$$\delta_{50} / \delta_0 = 1 + at^N \tag{5}$$

where δ_0 is the actual value of the initial deflection measured 1 min after commencement of loading, δ_{50} is the creep deflection after 50 years estimated by the power law, and a is A/δ_0, which is the relative creep one day after loading. The δ_{50}/δ_0 is the relative creep after 50 years.

Table 4. Creep Coefficients of Power Law Model

Material type	Estimated parameter		Correlation coefficient
	A	*N*	R^2
BPP	3.03	0.08	0.9675
BLVL	2.97	0.04	0.9382

The values of a (=A/δ_0), N, and δ_{50}/δ_0 obtained from the calculated curves (Fig. 6) and constants from 45 days to 90 days are shown in Table 5. As shown, the ratio δ_{50}/δ_0 became rather stable when the measuring terms were longer than 2 years for BLVL and 3 years for BPP. These results indicate that the minimum creep testing duration needed to estimate an accurate long-term curve of real-sized glulam is 2 years for BLVL and 3 years for BPP. According to the standard for structural design of timber structures (Architectural Institute of Japan 2006), the standard value should be smaller than 2. This means that the long-term performance of BLVL and BPP is beyond the safety limit by this dimension.

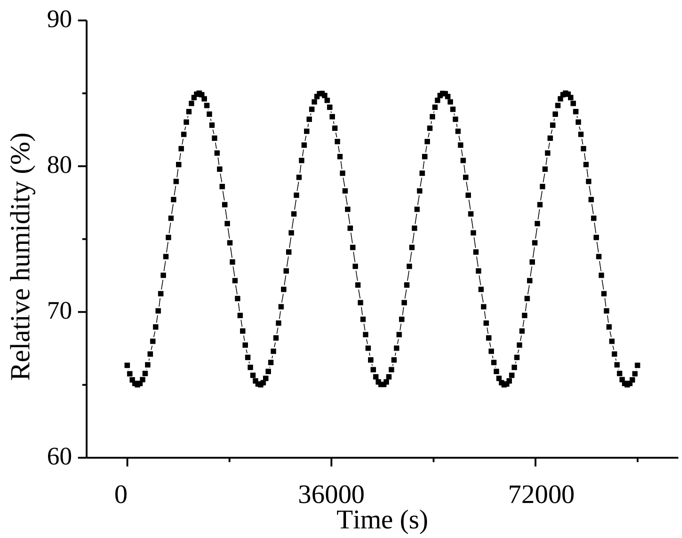
Table 5. Power Law Constants Estimated for Eq.5 using Data from Three Measuring Terms Representing Different Creep Stages

Material type	Constants for day 1 to day 90			Constants for day 15 to day 90			Constants for day 45 to day 90		
	$a=A/\delta_0$	N	δ_{50}/δ_0	$a=A/\delta_0$	N	δ_{50}/δ_0	$a=A/\delta_0$	N	δ_{50}/δ_0
BPP	1.0134	0.0862	2.9605	0.8453	0.1319	3.2718	0.8557	0.1293	3.1113
BLVL	1.0892	0.0258	2.3271	1.0115	0.0446	2.4129	1.0052	0.0463	2.3890

$a = A/\delta_0$, relative creep one day after loading; N, deceleration exponential; δ_{50}/δ_0, relative creep in 50 years

Mechano-Sorptive Creep

The purpose of performing experiments in varying conditions is to investigate the dependence of the mechano-sorptive effect on the bamboo composite materials (Liu 1993). The experimental results of creep in a varying environment are shown in Fig. 7.



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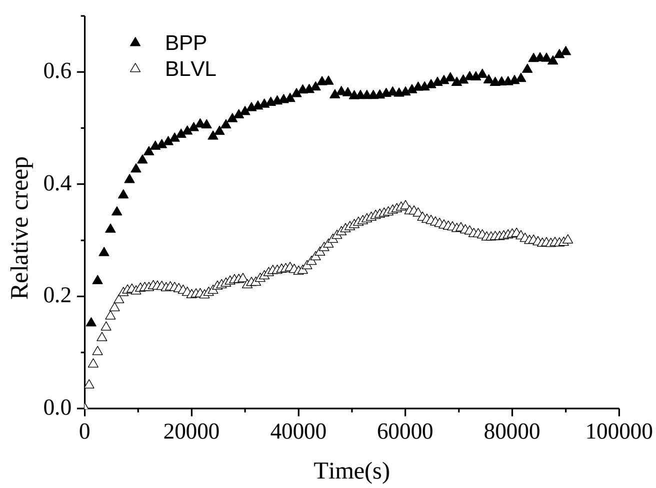

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Fig. 7. Relative humidity (a) and relative creep (b) of two boards

Table 6. Average of Creep Deflection and Comparison of ΔJ between the First and Fourth Humidity Cycles of Two Boards

Material type	Initial deflection (mm)	Final deflection (mm)	Increase in compliance(ΔJ)			
			First cycle(ΔJ_1)	Second cycle(ΔJ_2)	Third cycle(ΔJ_3)	Fourth cycle(ΔJ_4)
BLVL	0.2140	0.2989	0.001571	0.000951	0.000359	0.000689
BPP	0.3126	0.5093	0.005712	0.000909	0.000060	0.000566

According to Table 2 and Table 6, BLVL showed a creep deflection of 1.40 times the initial deflection after 4 humidity cycles, which was larger than that (1.31 times) of 3 months in uncontrolled humidity. Similarly, BPP showed a creep deflection of 1.63 times the initial deflection by same humidity cycling, also larger than that (1.51 times) in uncontrolled humidity. Compared with the creep curve in a constant environment, the creep deformation changed more dramatically under varying environment.

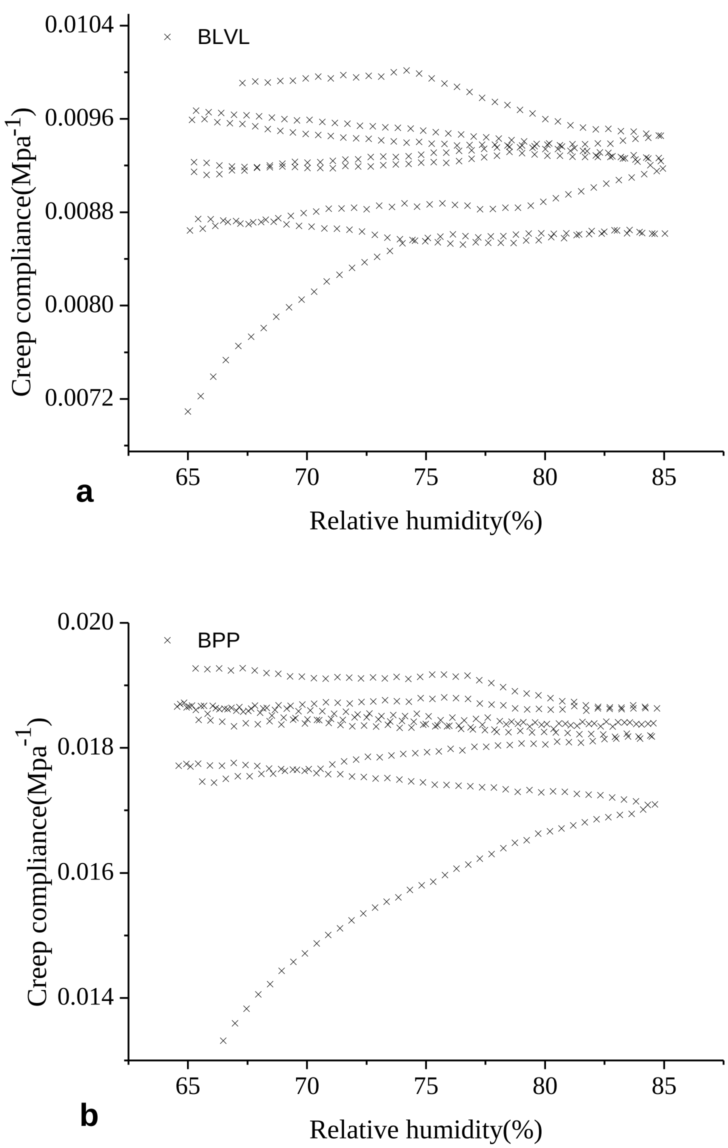

Fig. 8. Creep compliance of BLVL(a) and BPP(b) against moisture content

The incremental increases of compliance during each cycle gradually decrease except third cycle (Table 6). The creep compliance ($J(t)$) was defined as,

$$J(t) = \frac{\varepsilon(t)}{\sigma} \tag{6}$$

where $\varepsilon(t)$ is the creep strain at time t and σ is constant stress.

This observation is slightly different from the creep of wood because there is a limiting creep value above which the creep compliance will not go in the case of wood (Hunt and Shelton 1988). And comparison with wood, there is a cross-superposition phenomenon in the creep compliance of second cycle and third cycle (Fig. 8). These results may because of a shorter time to attain moisture equilibrium of each cycle. Then it is important to add humidity cycles and cycle time in further work.

CONCLUSIONS

1. In a constant environment, the mean values for relative creep of BLVL ranged between 0.105 and 0.31. The relative creep of BPP was from 0.15 to 0.51. Two creep curves were successfully simulated with the Burgers model and the power law model. The multiple correlation values of the Burgers model were good for the two boards, but BPP provided a better overall fit to the data. The minimum creep testing term to estimate an accurate long-term curve of real-sized glulam, is 2 years for BLVL and 3 years for BPP.
2. Under varying conditions, BLVL showed a creep deflection of 1.40 times the initial deflection after 4 humidity cycles, and BPP showed a creep deflection of 1.63 times the initial deflection by same humidity cycling, both larger than that in uncontrolled humidity. The incremental increases of compliance during each cycle gradually decrease.
3. According to the parameters of Burgers model, the anti-creep property of BLVL was better than that of BPP.

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