Investigation of the Creep Property of Fast-growing Poplar Wood Modified with Low Molecular Weight Resins

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Fast-growing poplar wood was modified with low molecular weight urea-formaldehyde resin (*UF*) at 41.5% concentration or phenol-formaldehyde (*PF*) at concentrations of 15, 25, and 40%. The physical and mechanical properties were measured, and creep behavior tests were carried out under ambient indoor conditions. The specimens were subjected to 30 and 50% of their maximum bending load. The density, modulus of elasticity, and modulus of rupture of *UF*-wood increased by 37.16, 45.86, and 28.36%, respectively, and the corresponding increases in 15% *PF*-specimen were 39.41, 31.80, and 27.74%, respectively. The wood modified with resins exhibited less creep deflection. The relative creep deflections of modified wood were about 0.22, 0.53, 1.22, and 0.32 times those of the untreated specimen at 30% of stress level after 15% *PF*, 25% PF, 40% *PF,* and *UF* were added, respectively. At the lower loading level, the relative creep deflection of the 15% *PF* specimen was 63.94% that of the 41.5% *UF*-specimen. Specimens treated with *UF* at 30 and 50% loading were broken within 120 d and 80 d respectively, whereas the untreated specimen was broken within one month at 50% loading.

Keywords: Fast-growing poplar; Low molecular resin; Elastic mechanical property; Creep; Durability

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INTRODUCTION

Static mechanical performance and creep behavior are two important properties of wood for many structural applications. Wood and wood-based materials exhibit viscoelastic creep and display time-dependent behavior. This characteristic creep distinguishes wood from other structural materials. Under varying environmental conditions, wood under a load tends to become more deformed over time. Excessive deformation poses serious safety concerns and may lead to structural failure (Gerhards 2000; Rosowsky and Bulleit 2002). Because creep often limits certain materials' use in practical applications, the creep exhibited by wood and wood composites has been extensively studied throughout the past several decades.

Chemical modification aims to improve wood properties by altering the basic chemistry of the cell wall (Epmeier and Kliger 2005), and has been performed to improve some wood and wood-based materials' durability. Wood modification with anhydride or thermosetting resin has been shown effective in reducing the rate of moisture sorption and moisture excluding efficiency (Feist *et al.* 1991; Deka and Saikia 2000; Chauhan *et al.* 2001; Chang and Chang 2002; Papadopoulos and Hill 2003). Chemical modification of wood with low-molecular weight phenol-formaldehyde resin (*PF*), melamine

formaldehyde resin (*MF*), or urea-formaldehyde resin (*UF*) could increase its mechanical properties, such as *MOR* (modulus of rupture) and *MOE* (modulus of elasticity) (Deka and Saikia 2000).

Larsson and Simonson (1994) dealt with the effect of acetylation on equilibrium moisture content of wood materials. The results showed that the chemical modification principle was the reduction of hydrophilic nature and could be used to improve dimensional stability of wood. Deformation of solid wood, including bowing, crookedness, and twisting, under varying humidity conditions can be strongly reduced by acetylation. They also concluded that the changes in mechanical performance involved reductions in *MOE* in the 6 to 17% range for pine wood but up to 7% increases in *MOE* for spruce wood. Yano *et al*. (1993) reported that acetylation can greatly reduce mechano-sorptive creep deflection and variability in moisture content for small, defect-free specimens of acetylated spruce wood; both the reductions can be up to 50%.

MF, *PF* and *UF* are belong to thermosetting resins. According to the research from Rapp (1999), the stabilization mechanisms of wood were explained as physical bulking and the combination of hygroscopic hydroxyls with the cured resin in the cell wall. Regarding mechanical properties, the improvements could be caused by an increase in density, but it might also be related to the temperature and chemical type (Van Acker and Stevens 1998). Rapp (1999) mentioned increases in hardness with the retained amount of resin, along with improved dimensional stability. Deka *et al*. (2002) found that modification of a fast-growing hardwood specimen with *MF* at a *WPG* of about 32% increased the *MOR* by 19% and the *MOE* by 10%. Van Acker and Stevens (1998) dealt Scots pine sapwood and beech wood with 10% *MF* and put forward that higher density without an increase in strength resulted in a smaller strength/density ratio.

In addition to conventional studies about strength, numerous studies of the long-term strength of wood-based materials have been carried out. Dinwoodie *et al*. (1984; 1991), Pierce *et al*. (1979), and Lee and Liu (2007) investigated the effects of wood species, load levels, load values, and conditions on the creep behavior of wood composites. Chen and Lin (1997) studied the relationship of wood modification and creep properties and established a creep model to predict the creep deflection under different modification conditions. Long-term weather resistance tests (Fan and Yu 1995; Tu and Shao 2008) have shown that the bonding strength of *UF*-based wood composites was very low and negligible after natural aging tests, while *PF*-based composites maintained more than half of their initial strength. The bending creep deflection was studied due to its importance and ease of measurement. Many models have also been developed to simulate long-term creep behavior. The Burger or Burger-based models (Pierce and Dinwoodie 1977) have been recognized as being effective in fitting and predicting creep deflection. The viscoelastic deflection was linear, but the viscous was non-linear in total deflection. Some earlier experiments indicated the creep deflection was linear and the non-linear tendency of creep deflection was not particularly clear when the loads are below 30% of the ultimate strength, and the higher load level can be applied to evaluate the nonlinear creep behavior (Tong 1993, 1994; Hunt and London 1989). Numerous studies about mechano-sorptive creep behavior have been conducting (Boyd 1982; Hoffmeyer and Davidson 1989; Mårtensson 1994; Mohager and Toratti 1993; Hanhijärvi 1995; Bengtsson and Kliger 2003), but the mechanism and essence of the mechano-sorptive effect on creep behavior was still not fully revealed. So an assumption in the creep results presented earlier was that modification would reduce mechano-sorptive creep.

Wood modification and creep studies are well-documented. Various analytical models have also been proposed to describe the observed creep behavior. In China, fast-growing poplar is valuable and widely-cultivated, especially in the central and eastern part of China. This plantation poplar has lower density and relatively low strength. It is not suitable for use in some structural applications. One possibility to overcome these drawbacks is chemical modification treatment with thermosetting resins. Little creep deflection data regarding modified fast-growing wood are available. The applicability of creep deflection models to describe time-dependent behavior has yet to be evaluated. This work focuses on investigating long-term durability of *PF*-modified fast-growing poplar wood and investigating the creep response of the modified wood as influenced by resin types and resin content.

To precisely analyze the creep behavior, the creep tests were conducted in the controlled conditions, but it's hard to consult for practical projects because of different conditions. In view of this situation, we are seeking the relationship between academic research and project application. The objectives of this study were to evaluate the impact of *UF* and *PF* on the static flexural properties of fast-growing poplar wood; to evaluate the effect of resin concentration on the creep; and to analyze the deflection pattern of modified poplar wood under long-term loading.

EXPERIMENTAL

Materials

Low-molecular weight resins of *UF* with 41.5% concentration and *PF* with concentrations of 15, 25, and 40% were used to impregnate poplar wood. The formula and synthetic process of resins were carried out in accordance with Xia *et al.* (2008) and Na *et al*. (2009). The original solid content of the *PF* resin was 47.5%. The pH of the *UF* and *PF* resins were 9.1 and 10.7, respectively. Their viscosities were 17.5 and 15.8 s at 20 °C according to GB/T 2794, respectively. Resin was stored at 0 to 5 °C to slow the curing rate until use. Before each test, the resin was homogenized for 5 min using a mixer running at a pumping capacity of 200 L/min.

The fast-growing poplar sapwood boards were cut and selected from trees obtained from Jiangsu province, Southeastern China. The trees were 13 years old and 38.3 to 45.7 cm in diameter at breast height. The logs were relatively straight. Defect-free boards were chosen from wood with average annual ring widths of 28.5 to 31.5 mm. The average initial moisture content of these specimens was measured as 12% by oven-drying. The specimens were conditioned at 20 °C and 65% *RH* for 2 to 5 d before they were impregnated with resins.

Methods

Wood Modifications

Full-size wood specimens with dimensions 38 by 180 by 3050 mm^3 were impregnated with resins. The wood specimens were subjected to a 15 kPa vacuum for 4 h. After that, they were immersed in the modifier at 450 kPa and 50 °C for 5 h. Excess modifier was removed under a 15 kPa vacuum for another 30 min. After impregnation, the specimens were placed on glass rod supporters in a tray to be air-dried at room temperature for 7 d. The specimens were placed in an oven at less than 60 °C for 12 h to achieve 14 to 20% moisture content.

After impregnation treatment, the following process was resin polymerization. The specimens modified with *UF* were treated for 5 h at elevated temperatures from 80 to 100 °C, and those modified with *PF* were treated for 5 h at temperatures between 80 and 140 °C. Because of the large variability in wood permeability, the outer and core material may be impregnated with varying degree. The test specimens chosen had similar weight gain after impregnation to achieve more consistent results. All specimens selected were weighed and recorded. The weight difference between the specimens was controlled to less than 5% in each test. The moisture contents of the modified samples were controlled to within 14 to 20%. After drying, the material was cut into pieces.

Tests for physical and mechanical properties

The densities and weight percent gain (*WPG*) were determined using oven-drying. *WPG* was defined by Eq. 1,

$$WPG = \frac{m_t - m_0}{m_0} 100 \quad (1)$$

where *WPG* is the solid content of the resin impregnated into the specimen (%), m_t is the oven-dried weight of the treated specimen (g), and m_0 is the initial, oven-dried weight of the specimen before treatment (g).

The bending properties tests were carried out according to GB/T 1936.1 (2009) and GB/T 1936.2 (2009). The specimens used for static flexural property testing were cut to dimensions of 20 by 20 by 300 mm^3 (radial by tangential by longitudinal) and conditioned at 20 °C and 65% *RH* for more than 10 d until constant weight was reached.

The length, width, thickness (±0.02 mm), and weight (±0.01 g) of twenty pieces were measured. The static bending strength (modulus of rupture, *MOR*, and modulus of elasticity, *MOE*) was measured. The tests were conducted using a universal wood-testing machine with a 50-N load cell. MC was measured based on the oven-dried weight after testing.

The *MOE* was experimentally determined by the slope of deflection and bending load that ranged from 200 to 400 N. The speed of bending load was set 3 mm/min.

Tests for creep behavior

The bending creep of specimens was tested at indoor uncontrolled conditions. To evaluate the nonlinear creep behavior, the higher load levels were applied. Testing was carried out as detailed in Table 1.

Table 1. Conditions of Creep Properties of Specimens

Specimen size	15×30×320 mm^3 (radial × tangential × longitudinal)
Specimen types	3 types: untreated, modified with *UF*, and modified with *PF*
Conditions before creep test	21 ±2 °C, 65 ±5% *RH* for 10 d
Number of specimens	3 in each group
Test type	Bending under central concentrated dead load
Load levels	30 and 50% of maximum load at rupture from static bending
Load span	300 mm
Load duration	19 weeks
Uncontrolled indoor conditions	Temperature and *RH* ranging from 16 to 31 °C and 40 to 80%

Creep deflections were measured and recorded manually at the bottom of each specimen at the midspan using a mounted dial gauge. After the load was imposed on the specimen, the deflection was recorded at 5 s intervals during the first 12 h, 15 s intervals for the next 2 d, and hourly for the following 1 week. For the rest of the testing period, one creep deflection reading was made daily.

RESULTS AND DISCUSSION

Physical and Static Mechanical Properties

The resin uptakes and some physical and static mechanical properties of the specimens obtained are presented in Table 2. The force-displacement curves obtained in bending tests are shown in Fig. 1.

Table 2. Physical and Static Mechanical Properties of Wood Specimens

Material type	Untreated specimen	*UF*-Modified Specimen	*PF*-Modified Specimens		
		41.5%	15%	25%	40%
WPG (%)	-	53.97* (14.86%**)	23.04 (14.87%)	37.83 (18.50%)	61.13 (21.09%)
Density (g/cm^3)	0.444 (8.58%)	0.609 (13.79%)	0.619 (12.26%)	0.646 (11.43%)	0.687 (10.85%)
MOE (MPa)	4351.36 (11.37%)	6347.04 (18.55%)	5735.12 (20.55%)	6596.38 (16.45%)	7459.37 (16.45%)
MOR (MPa)	47.22 (8.42%)	60.61 (20.32%)	60.32 (19.50%)	66.85 (12.07%)	72.56 (18.46%)

* The data in the table are the average of 15 replicate tests.
** The data in parentheses are the coefficients of variation.

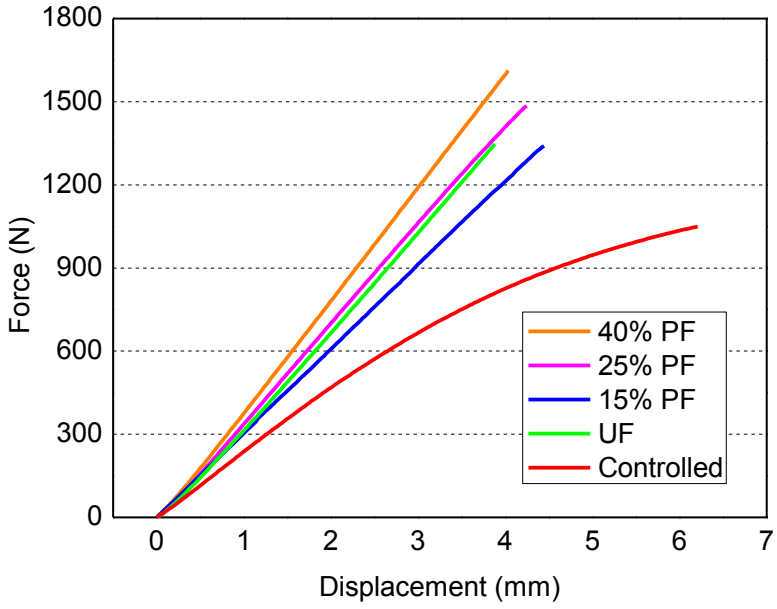

Fig. 1. The curves of force and displacement in bending test

As can be seen in Table 2, significant *UF* and *PF* uptakes were observed. The coefficients of variation of physical and mechanical performance of each group were bigger than that of control group, but were accepted considering the introduction of some more complex variables and its positive effect on mechanical properties of wood materials.

The *WPG* of specimens modified with 41.5% *UF* reached 53.97%. The *WPG* of specimens modified with 15, 25, and 40% *PF* were 23.04, 37.83, and 61.13%, respectively. The relationship between *WPG* and resin concentration was positively correlated, as was the relationship between density and resin concentration. The *WPG* of the specimens prepared with 40% *PF* was 1.65 and 0.62 times those of the 15 and 25% *PF* specimens, respectively. The resin concentration can be used to control the *WPG* and density of modified specimens. Poplar wood exhibited satisfying penetrability using the vacuum impregnation process.

The results also showed that modification significantly improved the static flexural properties. The *MOE* and *MOR* of the specimens treated with *UF* and *PF* were significantly higher than those of the untreated specimens. The *MOE* and *MOR* of the specimens treated with higher concentrations were also significantly higher than those of the specimens treated with lower concentrations. The *MOE* and *MOR* of specimens treated with 41.5% *UF* were 45.86 and 28.36% higher than those of the untreated specimens, respectively. The density, modulus of elasticity, and modulus of rupture of the specimens were 39.41, 31.80, and 27.74% higher after modification with 15% *PF*, respectively, and these properties further increased with *PF* concentration. The corresponding physico-mechanical values of specimens treated with more than 25% *PF* were stronger than those treated with 41.5% *UF*. When specimens were treated with 40% *PF*, these values grew to 12.81, 17.53, and 19.72%, respectively. The effect of *PF* was more obvious than that of *UF*.

Fourier transform infrared spectroscopy (FT-IR) spectra of wood treated with *PF* resin showed that cross-linking reactions took place within the cell wall (Liu *et al* 2000). Ryu *et al.* (1993) suggested that low molecular weight resin interacts with the hydroxyl groups of wood constituents through the formation of hydrogen bonds. Gindl *et al.* (2004) found that the impregnation of resin into the cell membrane caused a hardening of the structure. It has also been reported numerous times that impregnation of thermosetting resins into wood increases both its *MOR* and *MOE* (Deka and Saikia 2000; Pizzi 2003). Chemical modification is an effective approach implemented to increase wood's mechanical properties (Mourant *et al.* 2008).

During impregnation, *UF* and *PF* resins enter the lumen and the low molecular weight resins gradually infiltrate the cell walls (Araya 1997; Furuno *et al.* 2004). At 40% *PF*, the resin adsorbed was 13.27% greater and was more than in the samples treated with 41.5% *UF* because of different structure of resin. The benzene ring structure of *PF* played an important role in increasing resin uptake (Tang *et al.* 2003). Materials with similar structures are usually compatible, resulting in additional uptake into the microfibrils of the wood.

It was also noted that polymerized adhesive components infiltrate cell walls more deeply than the adhesive components, which only occupy the lumen. Cured resin in cell walls yields greater mechanical property improvement than it does when cured in the lumen because there are more chemical and physical bonds between the resin and wood. *PF* was more suitable and effective for use as a wood modifier to achieve higher strength than *UF* was.

Creep Behavior

Modification also changed the bending creep behavior of the poplar wood. An obvious reduction in bending deflection was observed. Williams (1981) reported that wood modification reduced the mechano-sorptive creep of wood. Analysis of the creep development and a defection curve were done to determine the interaction between the outer and inner parameters and their effects on creep behavior. Mean bending deflection curves are plotted in Figs. 2, 3 and 4.

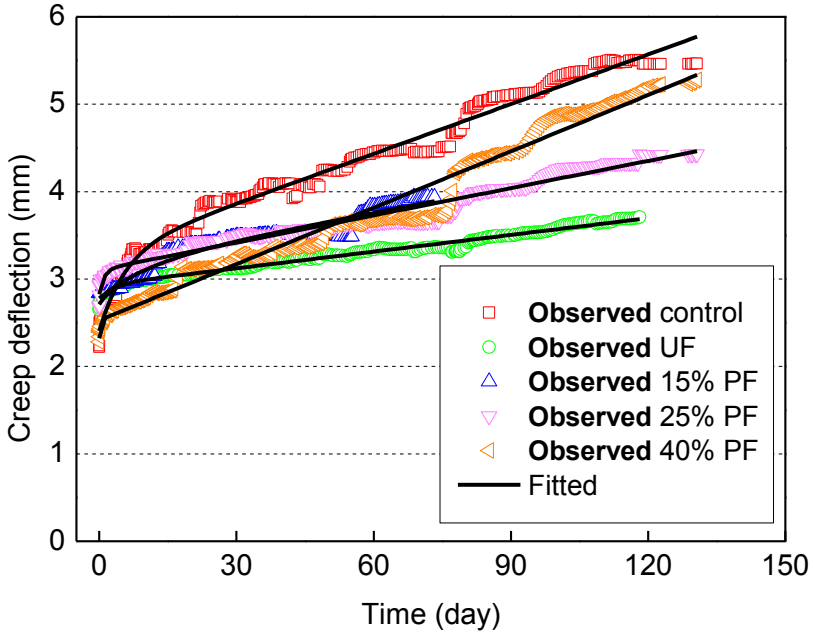

Fig. 2. Model fitted to creep deflection data at 30% loading: for control, *UF*, 15% *PF*, 25% *PF* and 40% *PF* specimens; the goodness of fit values were 0.985, 0.984, 0.964, 0.972 and 0.976.

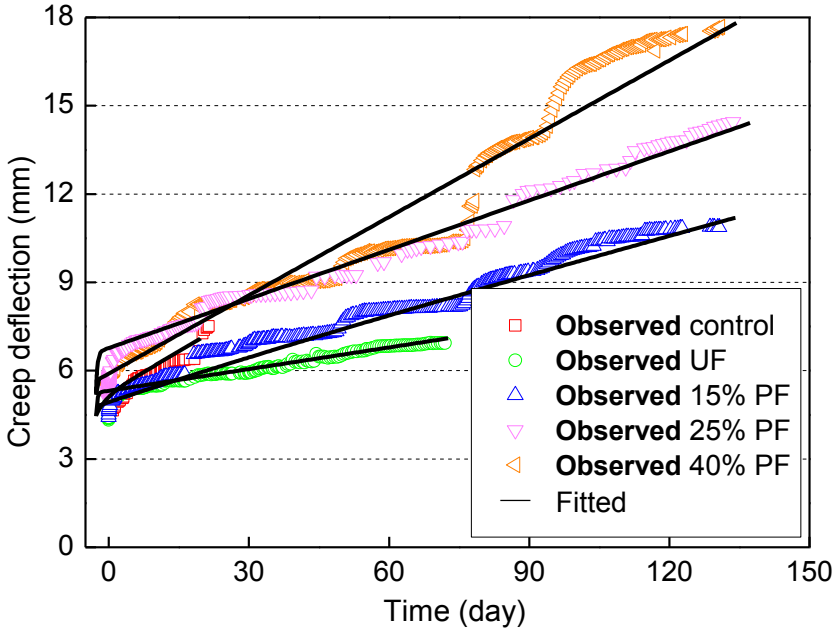

Fig. 3. Model fitted to creep deflection data at 50% loading: for control, *UF*, 15% *PF*, 25% *PF* and 40% *PF* specimens, the goodness of fit values were 0.968, 0.990, 0.988, 0.995 and 0.950.

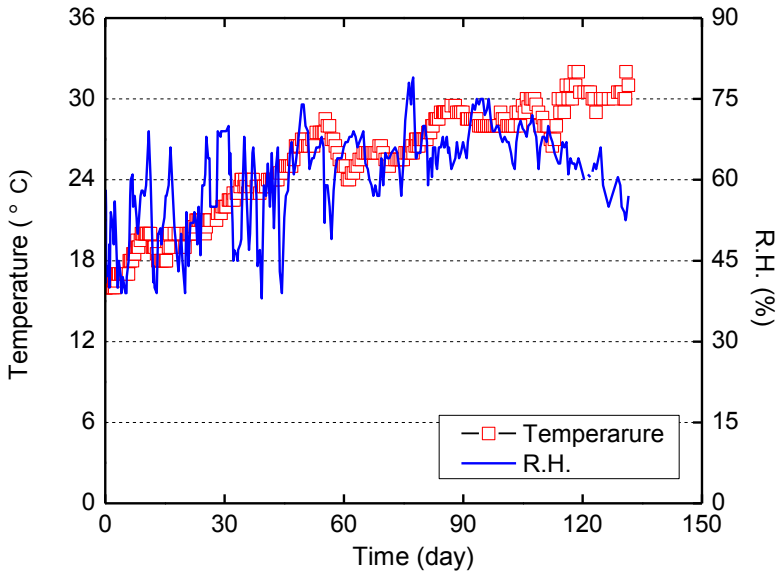

Fig. 4. Temperature and relative humidity (R.H.) changes over time during creep deformation test

In Figs. 2 and 3, the effect of modification on creep behavior was regular and the tendency was clear. The long-term deflection of all wood specimens increased with time. At lower loads, specimens treated with *UF* had the shortest load period, while those treated with *PF* had the most stable creep properties. At higher load, the untreated wood had the shortest load period, followed by the *UF*-treated one. Specimens modified with *PF* exhibited some plastic features. Under the uncontrolled indoor conditions with fluctuating temperature and humidity, the specimens treated with *UF* had short endurance. Specimens modified with *UF* showed more brittleness than those that were untreated or *PF*-treated. The untreated wood material was the weakest and usually failed first. The specimens modified with *PF* exhibited more toughness and stiffness. Besides its high strength and modulus, the weather-resistant properties of the specimen modified with *PF* were also improved.

The strength of wood materials is attributed to fiber cluster strength and fiber tensile strength (Fei 2014). Fiber cluster strength is the transverse connection strength of wood materials. The connection between fibers in untreated wood is made by amorphous materials composed of hemicellulose and lignin. Outer shell materials play a role in transferring and dispersing stress (Fei 2014). Impregnating thermosetting resins between micro-fibers could enhance the transverse connection with strong chemical bonds and mechanical interlock. The improved load period of the treated specimens accounted for the chemical enhancement *via* connection between micro-fibers.

PF or *UF* resins react with the hydroxyl groups of wood constituents to form chemical bonds. In *UF*-based wood materials, free hydroxyl groups separate out during gradual dehydration from solidified *UF* resin. Some free hydroxyl groups, which do not fully participate in chemical reactions, still exist in the resins. Hydrophilic hydroxyl groups can cause moisture adsorption and desorption under fluctuating conditions. The cured resin shrinks and expands repeatedly as moisture is exchanged with the environment. The chemical bonds in cured *UF* tend to depolymerization and break because of its sensitivity

and instability to heat and vapor. It was found that, at the 50% stress level, the untreated and *UF*-modified wood were all broken in the initial and middle experiments, respectively, and the ultimate bearing time of the untreated and *UF*-treated specimens were less than one month and 80 d, respectively in this experiment. Comparatively, cured *PF* imparts better water vapor and heat resistance because of the stability and durability of the benzene ring structure.

The three components of creep deflection are the instantaneous elastic deflection, the delayed elastic deflection, and the permanent viscous deflection. Instantaneous elastic deflection is linear and comes from the deformation of loaded, crystallized, rigid micro-fiber frameworks (Yin 1996). Delayed deflection can be gradually restored over time. Loaded and curved molecular chains tend to be straight and stretched along the direction of the load. At the same time, the pendant group of the main fiber chain stretches along the direction of the external force. It can be gradually restored after the load is removed. The recovery behavior over time can be observed. The other deflection cannot be recovered and is labeled viscous deflection. This is due to broken hydrogen bonds in the material such that viscous deflection is permanent and irreversible. According to the analysis of the mechanical properties of the treated specimens, creep deflection can theoretically be reduced. The three types of creep deflection decreased with increased resin penetration and enhanced bonding between fibers.

As shown in Table 2, the mechanical properties of the specimens significantly increased after they were modified with the resins. The specimen modified with *PF* was strongest, followed by those modified with *UF*, and the untreated specimens were the weakest. The specimens modified with *PF* exhibited the highest endurance and bore the heaviest load at the same load level.

The Burger model can be used to explain the relationships between deflection, modulus, and time and can be used to estimate the deflection in the future. The fitted curves are shown in Figs. 2 and 3.

The four-factor Burger model is shown in Eq. 2,

$$\varepsilon(t) = \varepsilon_0 + \varepsilon_c(t) = \frac{\sigma}{E_e} + \frac{\sigma}{E_d}[1 - \exp(\frac{-E_d}{\eta_d}t)] + \frac{\sigma}{\eta_v}t \quad (2)$$

where $\varepsilon(t)$ is the creep in time (d); ε_0 is the instantaneous creep in time (d); $\varepsilon_c(t)$ is the steady creep in time (d); σ is the static bending stress (MPa); E_e is the instantaneous modulus of elasticity (MPa); E_d is the delayed modulus of viscosity (MPa); η_d is the delayed coefficient of viscosity (MPa-day); and η_v is the viscous coefficient of viscosity (MPa-day)

Equation 2 can be simplified to,

$$\varepsilon(t) = \varepsilon_0 + \varepsilon_c(t) = A + B \cdot (1 - e^{-C \cdot t}) + Dt \quad (3)$$

where $A = \frac{\sigma_0}{E_e}$, $B = \frac{\sigma_0}{E_{de}}$, $C = \frac{1}{\tau} = \frac{E_{de}}{\eta_{de}} = \frac{\sigma_0}{B\eta_{de}}$, and $D = \frac{\sigma_0}{\eta_v}$.

From Eq. 3, the realtive creep deflection is as shown in Eq. 4,

$$\delta(t) = \varepsilon_c(t) / \varepsilon_0 = \frac{B \cdot (1 - e^{-C \cdot t}) + Dt}{A} \quad (4)$$

All parameters of the above formulae can be calculated. The long-term deflection of a typical specimen was predicted. To analyze the influence of the resin modification on the creep behavior, the fitted factors and predicted results are listed in Table 3.

Table 3. Creep Deflection of Specimens at 30% Loading

Specimen	Factor				Relative Creep Deflection (%)		
	A	B	C	D	1 a	10 a	50 a
Untreated	2.53622	0.85583	0.00863	0.00078	3.032	27.278	135.042
Modified with 15% *PF*	2.90622	0.45080	0.04055	0.00017	0.668	5.279	25.776
Modified with 25% *PF*	2.70583	0.40551	0.48710	0.00044	1.574	14.395	71.374
Modified with 40% *PF*	2.32288	0.20372	0.23980	0.00090	3.482	34.028	169.791
Modified with *UF*	2.74311	0.20523	0.03644	0.00027	0.937	8.697	43.186

The values in Table 3 were substituted into Eq. 3. The curves in Figs. 2 and 3 were good fits. The Burger model exhibited precision with over 90% fitting accuracy. Burger model was suitable for the fitting of the long-term deflection of the modified wood.

At the same load level, the elastic strain, *A*, was similar between the three materials. Because of the significant increase in maximum load, the treated specimens could sustain a greater load or sustain the same load with less deflection. Differences in the total creep deflection of each type of specimen mainly resulted from viscoelastic and viscous deflection over time.

Moisture and MC fluctuation with time are major factors that influence creep behavior of wood materials. Lower MC and less MC fluctuation can reduce the mechano-sorptive part of the creep deflection. The modified wood has lower MC and smaller MC fluctuation, so modified wood has less creep deflection than untreated wood. The environmental moisture expansion, swelling and shrinkage, occur predominantly in the transverse directions as related to the fiber, whereas mechano-sorptive creep occurs predominantly in the longitudinal direction of the fiber (Norimoto *et al*. 1992). So obvious jump-like creep deflection changes that are shown in Figs. 2 and 3 occurred as humidity fluctuated, as shown in Fig. 4. During moisture cycles, the initial adsorption caused an increase in the deflection. All the subsequent adsorption cycles generated less deflection at low or moderate stresses but increased deflection at high stresses. The above phenomenon showed that mechano-sorptive deflection at high stress level was more affected by MC fluctuations. During desorption, the increasing deflection was observed, as described by Hauska and Bucar (1996). The untreated specimens, with uninfluenced hydrophilic hydroxyl, were relatively more sensitive to moisture and MC fluctuations. As the MC fluctuated, the creep deflection increased with increasing MC because of the lower *MOE* and sensitivity to moisture of the untreated specimens.

Wood *MOE* is related to both the magnitude and the rate of creep. Specimens with a low *MOE* generally displayed greater creep deflection and a higher rate of creep. The modifications significantly reduced the creep deflection in this experiment. Compared with that of untreated wood, the bearing capacity of the modified specimen was greater. The half bearing capacity of untreated wood was slightly higher than 30% of that of the specimen modified with 40% *PF* and 41.5% *UF*.

As shown in Table 3, the relative creep deflections of modified wood were approximately 0.22, 0.53, 1.22, and 0.32 times that of the untreated specimen at the 30% stress level after 15%, 25%, 40% *PF*, and *UF* were impregnated, respectively. The relative creep deflection of the *PF*-specimen increased from 15.53 to 101.91% with increasing resin concentration. The relative creep deflection of untreated wood was almost as much as that of the 40% *PF*-specimen and the stress load of the specimen modified with 40% *PF* was 53.66% higher than that of the other wood. Specifically, the load of the specimens modified with 15% *PF* and 41.5% *UF* were almost equal at the same stress level, although the corresponding *WPGs* were 23.04 and 53.97%, respectively. However, the relative creep deflection of the 15% *PF*-specimen was 63. % that of the 41.5% *UF*-specimen. Modification with resin can lower creep deflection. Modification with *PF* yielded better creep deflection resistance in fast-growing poplar than modification with *UF* did.

CONCLUSIONS

1. Modification with low molecular weight *PF* or *UF* is an effective method to increase the density of poplar wood from 0.444 to 0.609 g/cm^3.
2. The mechanical properties of modified, fast-growing poplar wood were significantly improved when it was impregnated with *PF* and *UF*. The increases in the *MOE* and *MOR* with respect to the untreated wood were from 4351.36 to 5735.12 MPa and 47.22 to 60.32 MPa or more, respectively.
3. The effect of over 25% *PF* resin on strength was equal to or more than that of adding 41.5% *UF*, although the *WPG* effect was lesser. At similar resin concentrations, the *MOE* and *MOR* of specimens modified with *PF* were 17.53 and 19.72% higher than those of *UF*-modified resins, respectively.
4. There is a positive correlation between strength and the concentration of *PF* between 15 and 40%. Poplar wood with higher resin concentration was stronger. The *MOE* of 40% *PF*-specimen was 31.80, 51.59, and 71.43% more than those of 0, 15, and 25 *PF*-specimen, and *MOR* of 40% *PF*-specimen was 27.74, 41.57, and 53.66% more than those of 0, 15, and 25% *PF*-specimen, respectively.
5. The relative creep deflections of modified wood were about 0.22, 0.53, 1.22, and 0.32 times that of the untreated specimen at the 30% stress level after treatment with 15% *PF*, 25% *PF*, 40% *PF*, and *UF* were adopted, respectively. The relative creep deflection of untreated wood was almost as much as that of 40% *PF* and the stress load of the specimen modified with 40% *PF* was 53.66% higher than the other. Modification with resin could help lower the creep deflection.
6. At lower loadings, the relative creep deflection of the 15% *PF*-specimen was 63.94% that of the 41.5% *UF*-specimen. The effect of *PF* on creep deflection resistance of fast-growing poplar was much better than that of *UF*.
7. Specimens treated with *UF* at 30 and 50% loading all carried loads for within 120 and 80 d, respectively, and the untreated specimen was broken within one month at 50% loading. *UF*-treated wood exhibited the worst durability. Fast-growing poplar modified using existing techniques is not fit for brutal environmental conditions and structural application, even when *UF*-treated.

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