10th International Conference on
Wood & Biofiber Plastic Composites

IN: 10th International Conference on Wood & Biofiber Plastic Composites and Cellulose Nanocomposites Symposium : May 11-13, 2009, Monona Terrace Community & Convention Center, Madison, Wisconsin, USA. Madison, WI : Forest Products Society, c2010. 289 p. ISBN: 9781892529558

Characterizing Macroscopic Creep Behavior of Wood-Plastic Composites in Tension and Compression

S.E. Hamel, N.J. Bechle, J.C. Hermanson, and S.M. Cramer

Abstract

The polymers within wood-plastic composites (WPCs) are known to experience significant time-dependent deformation, or creep. While extensive work has been done on the creep behavior of pure polymers, little information is available on the effects of mixing the polymers with large amounts of wood or other bio-based fillers. As the market increases for structural WPC products that may be subjected to sustained loads, it is imperative that this creep behavior be understood. This study characterizes the time-dependent deformation of two WPC formulations [polypropylene and high-density polyethylene (HDPE)] in tension, compression, and flexure. It was found that the power law (Findley, Shapery, etc.) fits the data at various stress levels and loading mechanisms, for both formulations. This means that the deformation rate linearly decreases in log-log space and, after 400 d of testing; almost all the tests that have not failed remain in primary creep. The time-dependent constants associated with the power law and their stress dependencies are also presented.

Hamel:
Dep. of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA

Bechle:
Dep. of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA

Hermanson:
USDA Forest Products Laboratory, Madison, Wisconsin, USA

Cramer:
Dep. of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, Wisconsin, USA

Introduction

Wood-plastic composites (WPCs) have risen in popularity and acceptance in the past two decades and have steadily increased their market share in the construction industry (Clemons 2002). WPC producers have introduced extruded products that have found acceptance in secondary structural applications, such as decks and guard rails. These products have many advantages; for example, they can be made of recycled material, have low moisture absorption, offer good workability, and do not contain harsh chemicals like those in CCA-treated lumber (Manning and Ascherl 2007). Recently there has been demand for outdoor products that act as primary structural components, such as joists and girders, and these have begun to be developed (Smith and Wolcott 2006).

Several studies have been conducted to evaluate WPC's short-term strength and stiffness, mostly using currently existing ASTM standards designed for wood and wood composites (Costa et al. 2000, Stark 2001). Fewer researchers have looked at the longer time-scale behavior of WPCs. Those who have (Pooler and Smith 2004, for example) concluded that WPCs are nonlinear viscoelastic. Viscoelastic materials cannot be completely characterized using linear elastic short-term response parameters, such as modulus of rupture (MOR) and modulus of elasticity (E), alone. It is also necessary to adequately describe the time-dependent response of the material. For these reasons, it is critical to understand and be able to model the creep mechanics of WPCs. It cannot be assumed that existing wood-product standards and code requirements will adequately address the unique behavioral characteristics of wood-plastic composites.

Creep is the slow continuous deformation of a material subjected to a constant applied stress (Findley et

al. 1976). Time-dependent materials face two problems in structural applications: excessive deflection and ultimately creep rupture. While creep rupture clearly presents the greater danger, deflection concerns may have a larger impact on the viability and acceptance of the material. It has been shown that even at relatively low stresses WPC structural members may experience excessive deflections given enough time, while few attempts have been made to estimate their long-term deflection (Kobbe 2005, Lin et al. 2004). The current standards for WPC mechanical properties test the creep recovery and creep rupture of the material in flexure only (ASTM 2004). While important, these parameters are different from time-dependent strain and cannot be used characterize the creep response in tension and compression. Future standardized response parameters should be able to estimate long-term deflections and be used to improve the engineered shapes of the products.

The power law is one method of characterizing the long-term response of a material to a sustained load. It has been used extensively to describe polymer deformation (Findley 1976), including to describe WPCs (Sain et al. 2000). The power law is:

$$\varepsilon = \varepsilon_o + m\, t^n \qquad [\mathbf{1}]$$

Where ε is the total strain, m and n are material parameters, and ε_0 is the time-independent strain of the material. The material parameters are all functions of stress, temperature, and humidity. It has been noted (Michopoulos et al. 2007) that the tension and compression behavior of WPCs are very different. This phenomenon greatly enhances the complexity of the mechanics of materials analysis and introduces errors if ignored. This was confirmed for both short-term and 90-d behavior by Dura et al. (2005). Thus, the three material parameters in **Eq.** [**1**], m, n, and ε_0, will differ in tension and compression for a given material.

A few studies have included the investigation of tensile creep behavior of coupons (Doh et al. 2005), and one has reported compression properties (Dura et al. 2005). Most other studies have concentrated on the flexural testing; however, due to the mode-dependent nature of the material, flexure tests do not adequately characterize its constitutive response. In the present work, it will be shown that the power law holds for two WPC formulations at several stresses in both tension and compression. A method for determining the power law material parameters is presented and the resulting constants for the selected WPCs are shown.

Methods

Materials

Two WPC formulations were evaluated in this work: a polypropylene-based product and a high-density polyethylene (HDPE) composite. The former was produced as a research formulation by the Washington State University Wood Materials Engineering Laboratory. The extruded boards have a cross-section of a triple-celled box with 1.0 cm wall thickness. Total outside dimensions were 45 × 170 mm. They are made up of 59% pine wood flour, 34% polypropylene, 4% talc, and 3% processing additives. This formulation is further described by Kobbe (2005).

The HDPE formulation, which was extruded as a solid board that measures 150 mm × 25 mm, consists of 55% wood pine flour, 30% HDPE, and 2% proprietary coupling agent. The remaining 13% of the composite and details about the extrusion process are also proprietary. The HDPE formulation was produced by Strandex Corporation. All material proportions are by weight.

Short-Term Testing

To determine the short-term ultimate strengths of the materials, tests were performed on coupon specimens in both uniaxial tension and compression. The coupon specimens were cut and machined from the extreme fiber zones of both formulations such that the test direction was parallel with extrusion. The tension specimens were tested according to ASTM D638 (ASTM 2002a). The specimens were Type I specimens (50-mm gauge length) tested at a target rate of 1% strain min^{-1} using a servo-mechanical testing machine (Instron 5566) with self-aligning grips. The compression specimens were tested using the same equipment according to ASTM D695 (ASTM 2002b). Dog bone compression specimens were used to prevent localization effects at the boundary conditions. The specimens were of similar dimensions to those in ASTM D695, but the support jig was omitted. The specimen gauge length was reduced to 12.7 mm and the radii were reduced to 12.7 mm to prevent buckling. The specimens varied in thickness, but were not less than 10 mm. Deformation of the gauge length in both tests was measured using MTS Extensometers (634.12E-24). Additional tension tests were performed at a strain rate of 100% min^{-1} using a servo-hydraulic MTS testing machine and MTS 407 controller. Deformations were measured using Instron Extensometers (2630–004) with a 25-mm gauge length. Test data was recorded using a computer-controlled data acquisition system.

Long-Term Testing

Using the constitutive results of the short-term coupon testing, an ADINA finite element model was created for each formulation. The algorithm was used to simulate a 3-point bending test of smaller flexure specimens at a length-to-depth ratio of 16, subjected to a ramp loading to failure. To verify the constitutive models, the deflections of the analyses were compared to experiments conducted using the Instron setup discussed above and the models were found to be satisfactory. These models were then used to evaluate and predict the tension and compression components of a full-size flexural specimen

subjected to 4-point bending with a 2.13 m span. Using the results of this analysis, appropriate point loads were then determined to induce selected stress levels (20 and 50% of ultimate tensile strength) in the tensile face of the full-size specimen. The corresponding stress in the compression face was determined from the analysis and used as the corresponding compression stress. Due to higher ultimate strengths, the compression stresses in the flexural member are a much smaller proportion of the ultimate compression strength. For the sake of simplicity, the compression tests will be referred to as the 20 and 50% load levels for the remainder of this paper. The loads can be seen in **Table 1**. A 35% tension test was also added to increase the characterization of the more critical tensile behavior.

Coupon specimens for tension and compression testing were identical to those described for short-term testing. The load was applied using steel grips attached to a pneumatic cylinder and its piston rod (see **Fig. 1**). Each cylinder load was controlled with an electro-pneumatic regulator. The specimens were held using serrated grips that were tightened with 120 in/lbs of torque. For the tension setup, each pneumatic cylinder loaded two specimens. The load was applied at the center of a steel bar connecting the specimens such that an equal load was maintained in each specimen. In the compression setup, the load was applied directly to the grips by the piston rod. Deformation data of each specimen was collected using two Vishay metallic foil strain gauges (CEA-13–250UW-120) on opposing faces connected in a half-Wheatstone bridge. The gauges were attached to the specimens at the midpoint of the gauge length.

The flexural tests were conducted according to ASTM 6109 (ASTM 2005). Deflection information was collected using a linear variable differential transducer (LVDT) placed at mid-span. Data for all creep tests was recorded with a computerized data-acquisition program.

Two specimens were tested for each condition and the results were averaged. All tests were conducted in a climate-controlled room at 25°C and 50% relative humidity. The specimens were mounted in their grips, the grips were tightened to the required torque, and the load was immediately applied as quickly as possible. During the loading, most specimens experienced strain rates between 1% and 3% min^{-1}.

Results and Discussion

The constitutive response of WPCs to monotonic loading is well captured by the inverse hyperbolic sine function (Kobbe 2005) of the form:

$$\mathbf{e}_0 = \mathbf{e}_0^{+} \sinh^{-1} (\mathbf{s}/\mathbf{s}_0) \qquad [\mathbf{2}]$$

This response does not include a time-dependent term, but **Eq.** [**2**] can be substituted for the stress dependent

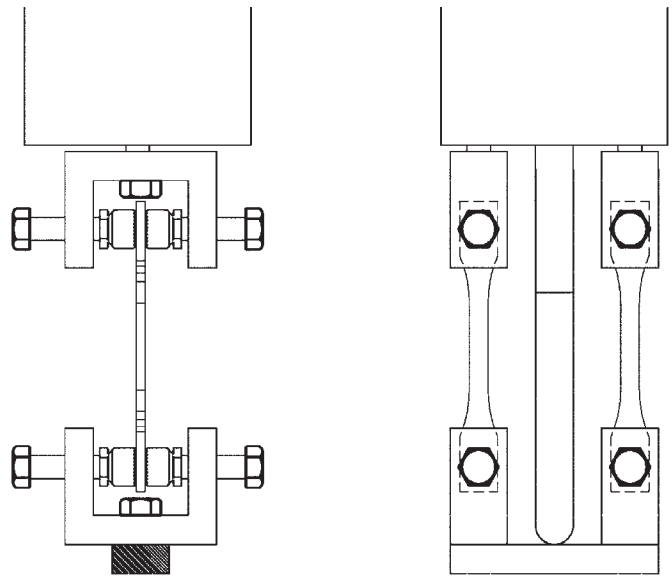

Figure 1a. ~ *Creep tension coupon testing apparatus.*

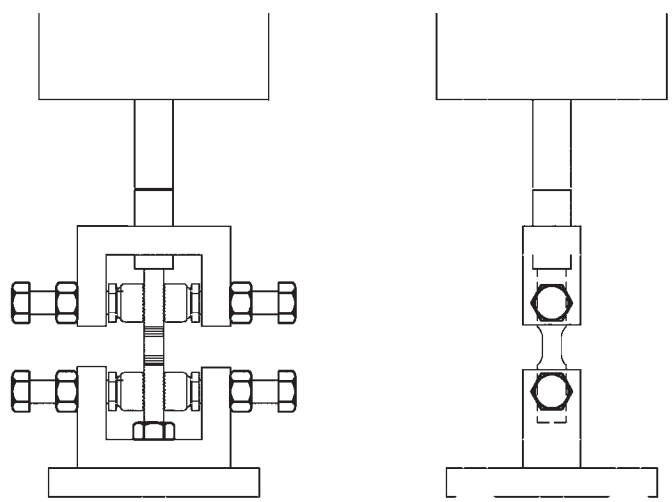

Figure 1b. ~ *Creep compression coupon testing apparatus.*

Table 1. ~ *Applied loads used in creep testing.*

Formulation	Ultimate tension	Tensile stress	Ultimate compression	Compression stress	Flexure load
	(%)	(MPa)	(%)	(MPa)	(N)
HDPE	20	4.62	11.6	4.54	1074
HDPE	50	8.07	29.3	11.44	2772
PP	20	4.14	10.8	5.80	837
PP	50	10.34	20.2	10.84	2168

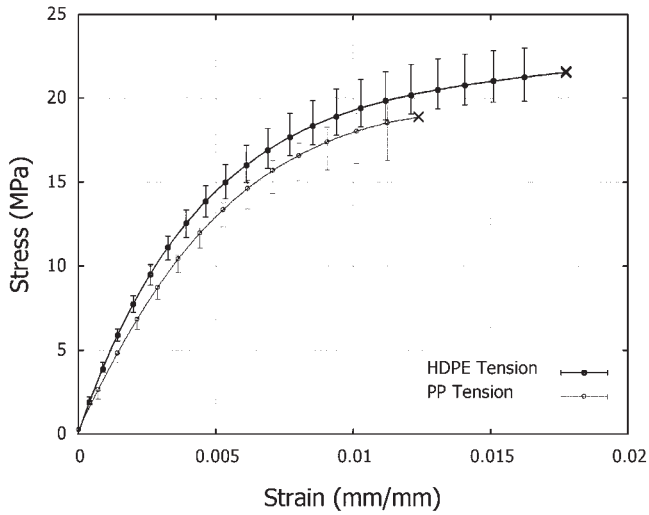

Figure 2a. ~ *Material constitutive response to monotonic tensile loading, head displacement rate of 5mm min^{-1}.*

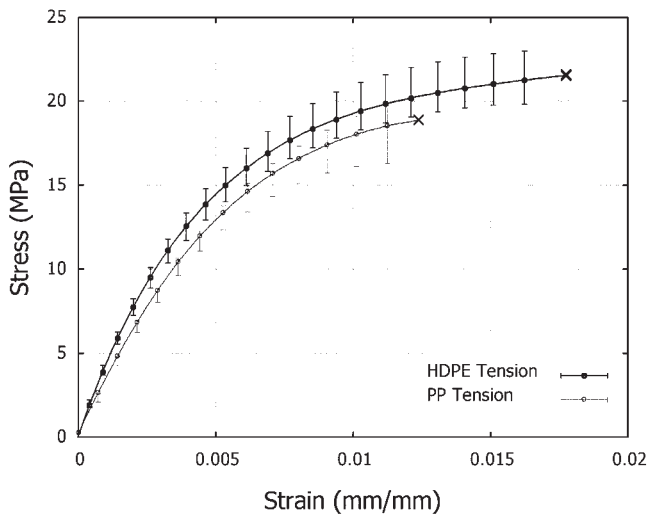

Figure 2b. ~ *Material constitutive response to monotonic compression loading, head displacement rate of 0.3mm min^{-1}.*

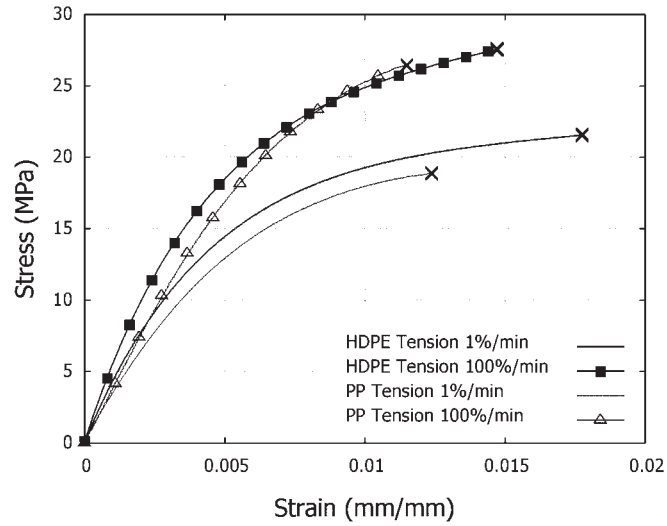

Figure 3. ~ *Material constitutive response to monotonic tensile loading, multiple strain rates.*

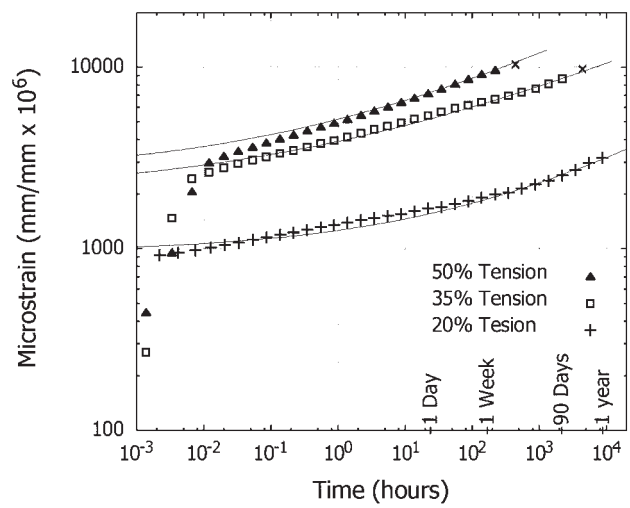

Figure 4. ~ *Strain response of WPC due to constant stresses and the corresponding power law fits.*
Figure 4a. ~ *HDPE formulation in tension.*

coefficients in the power law (Findley and Poczatek 1955). The full equation becomes:

$$\mathbf{e}(\mathbf{s},t) = \mathbf{e}_0^{+} \sinh^{-1}(\mathbf{s}/\mathbf{s}_0) + m(\mathbf{s})\, t^n \qquad [3]$$

Data from the monotonic loading tests in tension and compression can be seen in **Fig. 2**. Due to the relatively slow loading of 1% strain min^{-1}, the short-term response is not time independent, and **Eq.** [**2**] is incomplete. To determine the instantaneous tensile strain ($\mathbf{e}_0$) of the power law creep response, the constitutive responses from the 100% min^{-1} tests were used. The results of these tests can be seen in **Fig. 2**. At each stress in **Table 1**, the compliance of each monotonic test was evaluated to find the strain response and these strains were averaged.

Unfortunately, it was not possible to conduct compression testing at the higher strain-rate; instead, it was noted that for the stress range of interest, the strains from the 100% min^{-1} tests were 70 and 80% of the 1% min^{-1} tests for the HDPE and polypropylene, respectively. The comparison of these different strain-rates is shown in **Fig. 3**. These ratios were applied to the 1% min^{-1} compression test data to find the instantaneous compression responses. The resulting instantaneous strain values ($\mathbf{e}_0$) can be seen in **Table 2**.

The coupon creep responses of the two WPC formulations can be seen for various loading modes and stress levels in **Fig. 4**. Tension failure occurred for both formulations around 1% strain (shown with an "X" in the figures). For the HDPE formulation, this occurs in the tests at both 35 and 50% of ultimate strength. A nonlinear least-squares (NLLS) Marquardt-Levenberg algorithm (Crawford 2007) was applied to the average creep response to solve for the remaining constants of **Eq.** [**1**] at each stress. The instantaneous strain was held constant

Table 2. ~ *Power law material constants for various stress levels.*

Applied stress level	Stress	Power law fit parameters		
		e_0	m	n
	(MPa)	(me)	(me)	
HDPE				
20% Tension	4.46	954	308	0.215
35% Tension	8.81	1983	1927	0.162
50% Tension	10.92	2528	2654	0.184
20% (11.6%) Compression	4.19	749	709	0.136
50% (29.3%) Compression	10.50	2226	2954	0.137
Polypropylene				
20% Tension	3.90	900	362	0.17
35% Tension	6.93	1730	439	0.219
50% Tension	10.24	2655	1394	0.287
20% (10.8%) Compression	5.74	1264	283	0.217
50% (20.2%) Compression	10.10	2392	870	0.192

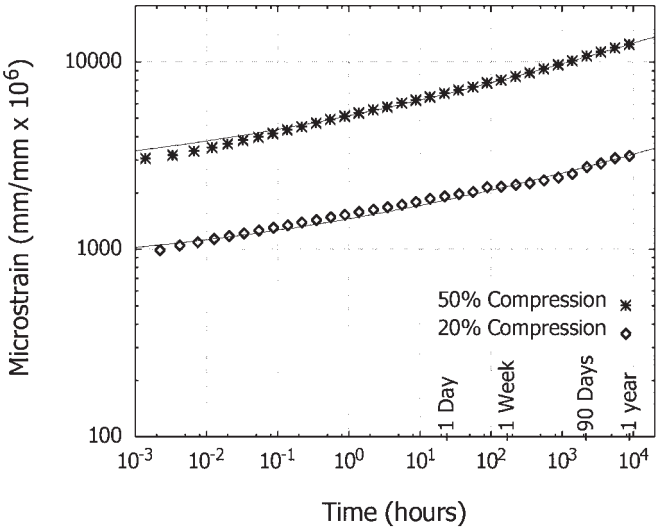

Figure 4b. ~ *HDPE formulation in compression.*

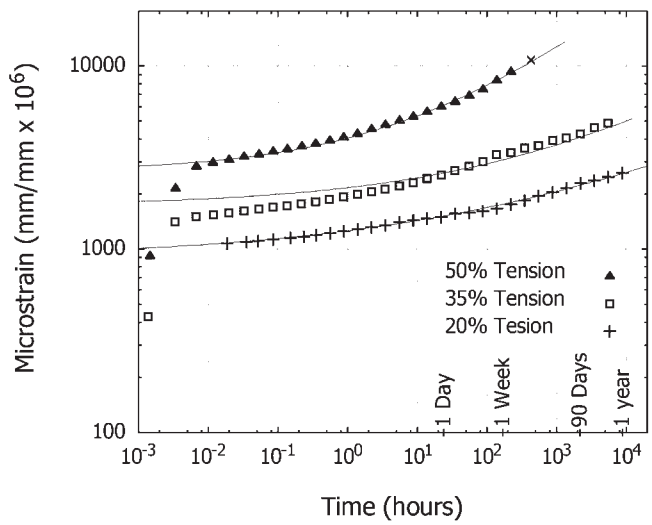

Figure 4c. ~ *Polypropylene formulation in tension.*

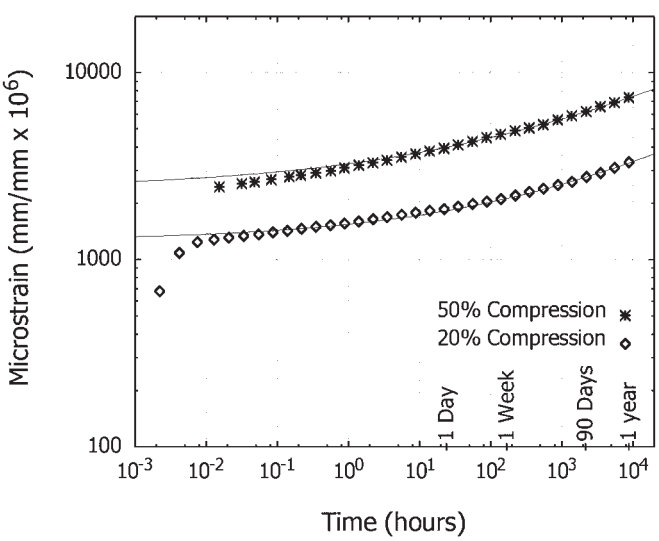

Figure 4d. ~ *Polypropylene formulation in compression.*

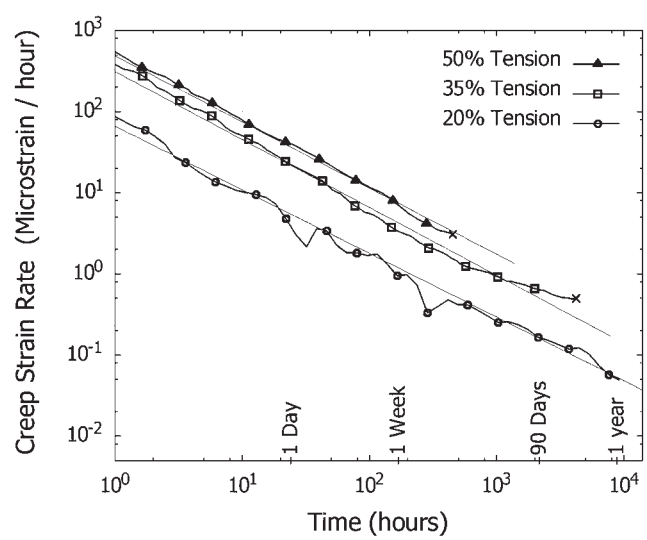

Figure 5. ~ *Strain rate responses of HDPE formulation coupons due to constant tension stresses and their corresponding power law fit.*

for each model and the two remaining parameters (m and n) were fitted to the data. The resulting material parameters can be seen in **Table 2** and the power law curves can be seen in **Fig. 4**.

The creep strain-rate of the power law model is linear in log-log space. This can be seen in **Fig. 5**, which shows a sample of the average creep strain rates for coupon tests up to 10,000 h (415 d). It is of note that the tension-creep response of the HDPE formulation at 35% of ultimate strength deviates from the linear fit at around 500 h. This indicates that the specimen is moving toward secondary creep, which is defined as a linear (in a non log-log plot) increase of strain with time. Other researchers have also reported secondary creep in HDPE at higher loads (Brandt and Fridley 2003). The increase in strain-rate may be caused by damage. It appears that the specimens at 50% of ultimate strength do not survive long enough to experience secondary creep. Neither the HDPE compression specimens, nor the polypropylene formulation coupons deviate from their linear log-log rate.

As expected, the material parameters are mode- (tension, compression) dependent. In addition, the time coefficient, m, is also strongly stress-dependent. The exponent, n, does not appear to be stress-dependent for the HDPE formulation or the compression of the polypropylene. The exponent term appears to be linearly dependent on the stress for the tensile mode of the polypropylene formulation. A larger number of stress levels is required to confirm a functional form of the stress dependencies of m and n.

Conclusions

The results of this work shows that the long-term creep response of two WPC formulations, one containing HDPE and the other with polypropylene, can be modeled well using the power law. Because the material constants of the power law for each material were found to be nonlinearly stress-dependent, it was confirmed that these materials behave in a nonlinear viscoelastic manner. It was also shown that specimens subjected to 50% of the ultimate tensile stress failed at a strain of 1% in a relatively short time. This research indicates that WPCs cannot be fully characterized by short-term testing. Any characterization of the material for engineering or evaluation purposes must contain a long term viscoelastic component. The power law presented here offers one simple method to achieve this characterization.

Acknowledgments

This project is supported by the National Research Initiative of the USDA Cooperative State Research, Education, and Extension Service, grant number 2005-35103-15230. The authors would also like to acknowledge Washington State University for providing the Polypropylene Formulation, and Arthur Gronvold of Ecole Normale Superieure de Cachan for help with testing.

Literature Cited

ASTM. 2002a. D638. Standard Test Method for Tensile Properties of Plastics. ASTM International, West Conshohocken, PA.

ASTM. 2002b. D695. Standard Test Method for Compressive Properties of Rigid Plastics. ASTM International, West Conshohocken, PA.

ASTM. 2004. D7031. Standard Guide for Evaluating Mechanical and Physical Properties of Wood Plastic Composite Products. ASTM International, West Conshohocken, PA.

ASTM. 2005. D6109. Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastic Lumber and Related Products. ASTM International, West Conshohocken, PA.

Brandt, C.W., and K.J. Fridley. 2003. Load-duration behavior of wood-plastic composites. J. Mat. Civ. Engr. 15(6):524–536.

Clemons, C. 2002. Wood-plastic composites in the United States: The interfacing of two industries. Forest Prod. J. 52(6):10.

Costa, T.H.S., D.L. Carvalho, D.C.S. Souza, F.M.B. Coutinho, J.C. Pinto, and B.V. Kokta. 2000. Statistical experimental design and modeling of polypropylene-wood fiber composites. Polym. Test. 19:419–428.

Crawford, Dick. 2007. Gnuplot: An Interactive Plotting Program. March 3. http://www.gnuplot.info/docs/gnuplot.pdf; verified 25 Nov. 2009.

Doh, G.-H., I.-A. Kang, S.-Y. Lee, Y.-T. Kong, C.-S. Jeong, and B.-S. Lim. 2005. Mechanical properties and creep behavior of liquefied wood polymer composites (LWPC). Compos. Struct. 68(2):225–233.

Dura, M., R.A. Lopez-Anido, H. Dagher, D. Gardner, S. O'Neill, and K. Stephens. 2005. Experimental Behavior of Hybrid Wood-Plastic Composite Fiber-Reinforced Polymer Structural Members for Use in Sustained Loading Applications. Forest Products Society, Madison, WI. pp. 131–137.

Findley, W.N. 1976. Creep and Relaxation of Nonlinear Viscoelastic Materials, with an Introduction to Linear Viscoelasticity. North-Holland Pub. Co., Amsterdam, The Netherlands.

Findley, W.N., and J.J. Poczatek. 1955. Prediction of creep-deflection and stress distribution in beams from creep in tension. J. Appl. Mech. 77:165–171.

Kobbe, R.G. 2005. Creep behavior of a wood-polypropylene composite. Masters of Science, Washington State University, August. http://hdl.handle.net/2376/363; verified 6 Jan. 2010.

Lin, W.S., A.K. Pramanick, and M. Sain. 2004. Determination of material constants for nonlinear viscoelastic predictive model. J. Compos. Mat. 38(1):19–29.

Manning, M.J., and F. Ascherl. 2007. Wood-Plastic Composite Durability and the Compelling Case for Field Testing. Forest Products Society, Madison, WI. pp. 217–224.

Michopoulos, J.G., J.C. Hermanson, and R. Badaliance. 2007. Characterizing Wood-Plastic Composites via Data-Driven Methodologies. Forest Products Society, Madison, WI. pp. 145–151.

Pooler, D.J., and L.V. Smith. 2004. Nonlinear viscoelastic response of a wood-plastic composite including temperature effects. J. Thermoplast. Compos. 17:427.

Sain, M.M., J. Balatinecz, and S. Law. 2000. Creep fatigue in engineered wood fiber and plastic compositions. J. Appl. Polym. 77(2):260–268.

Smith, P., and M. Wolcott. 2006. Opportunities for wood/natural fibre composites. Forest Prod. J. 55(2):1–11.

Stark, N. 2001. Influence of moisture absorption on mechanical properties of wood flour-polypropylene composites. J. Thermoplast. Compos. 14:421–432.