CREEP BEHAVIOR OF COMMERCIALLY PRODUCED PLASTIC LUMBER

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Abstract

Short-term creep tests were performed upon samples of lumber manufactured from recycled plastics by four different companies. In addition, stress-strain tests were carried out at various rates of strain over shorter intervals of time in comparison with the duration of the creep tests. A simple model uses data from the strain-rate tests to calculate creep strain as a function of time. Calculated values are in good agreement with experimental creep data. The results are examined in terms of morphological features. The feasibility of finding a method to calculate long-term creep properties is discussed.

Introduction

The ability to extrude a mixed plastic feedstock into lumber-like profiles for structural applications has spawned a number of recycled plastic lumber companies. These companies produce products with mechanical properties that vary widely from company to company, though the products have similar appearance.[1,2] The industry at this time has no standardized test methods for referral, which severely limits the products' applications. Significant progress has been made in this regard, and the first plastic lumber ASTM's are expected to be issued by the time of publication of this article. With these standards in place, a direct comparison can be made between different products. An area that has not received much attention is the time dependence of the mechanical properties of plastic lumber. Any attempt to design for long-term performance, utilizing ASTM stress-strain data will require large safety factors. Conversely, an accurate and rapid prediction of long-term performance of these products will allow for smaller safety factors and is an important key to efficient design. An understanding of time-dependent behavior is necessary in order to predict the long-term mechanical properties of plastic lumber in load-bearing applications.

An earlier work evaluated mechanical properties at a single strain rate to establish the mechanical properties for a number of participating manufacturers.[1] For the current study, selected groups of lumber were subjected additionally to a strain rate equal to two orders of magnitude greater than that used previously, and samples from these groups were subjected separately to creep tests.

A simple mathematical model is derived and used to predict creep strain for periods of time of up to 100 hours from the stress-strain data obtained at two rates of strain over time intervals ranging from 10 minutes to 10 hours (hereafter referred to as ramped tests). Agreement between calculated values and experimental creep data suggests the further development of a predictive method to be used to estimate truly long-term (~25 years) mechanical properties from short-term tests, thereby making unnecessary the impractical measurement of the long-term tests themselves.

Predictive Theory

Creep strain can be calculated from ramped experiments by following a simple model. Figures 1a and 1b show graphically the relations between stress σ and strain ε as a function of time t for the case of linearly ramped strain: at the time $t = t_r$, $\sigma = \sigma_r$, and $\varepsilon = \varepsilon_r$. Figures 2a and 2b illustrate graphical relations for stress and strain as a function of time for a typical creep experiment: $\sigma = \sigma_c$ = constant, and at the time $t = t_c$, $\varepsilon = \varepsilon_c$; also, we assume that the strain can be approximated by $\log \varepsilon = [\log K + (n_c)\log t]$, where n_c is the creep exponent, equal to the slope of log ε vs log t, and K is a constant. Since we seek to obtain creep data from ramped data, we assume that Figure 1a can be made similar in form to that of Figure 2a by finding the average value of stress $\sigma_{r,avg}$ over the time interval shown such that

$$\sigma_{r,avg} = \frac{\int_0^{t_r} \sigma(t)dt}{\int_0^{t_r} dt} \qquad (1)$$

where σ(t) can be obtained from a fifth-order polynomial fit to the ramped data. For comparative purposes, the constant stress $\sigma_{r,avg}$ can be applied over the interval t_r, as is shown in Figure 3a, quantitatively giving the same area under the stress-vs-time curve as for the relation of Figure 1a, and qualitatively agreeing in form with the true creep curve of Figure 2a.

A corresponding value of strain may be obtained similarly by calculating the average value of ramped strain over the time interval from t = 0 to $t = t_r$, which, for a linearly ramped test is equal to $\varepsilon_r/2$, and, which, to first order may be taken as the value of creep strain at time t_r for $\sigma_c = \sigma_{r,avg}$. However, unlike the case for transformed stress, the form of transformed strain vs time, shown in Figure 3b, is not identical to that of a true creep curve (Figure 2b). Specifically, a creep test shows an exponential increase of strain with time, characterized by a creep exponent typically on the order of 0.1 (for polyethylene).

One can obtain an improved estimate of creep strain by calculating the average value for the relation given in Figure 2b, or

$$\varepsilon_{c,avg} = \frac{\int_0^{t_c} Kt^{n_c} dt}{\int_0^{t_c} dt} = \frac{\varepsilon_c}{n_c + 1} \qquad (2)$$

Using equation (2), the true creep curve (Figure 2b) can be transformed into a form (Figure 4a) identical to that of Figure 3b. Comparing these and equating the strains, $\varepsilon_r/2$ and $\varepsilon_c/(n_c+1)$, we obtain an improved relation for creep strain in terms of ramped strain, $\varepsilon_c = (\varepsilon_r/2)(n_c+1)$ at $t = t_r = t_c$ (Figure 4b). So as to maintain the requirement that we calculate creep strain solely from ramped data, we estimate n_c for a given material and stress by using the first-order calculated values of strain, $\varepsilon_r/2$, at time $t = t_r$, calculated from each of the two strain rates, one rate being 100 times the other, or

$$n_c \approx \frac{\log \frac{\varepsilon_r 2}{\varepsilon_r 1}}{\log \frac{t_r 2}{t_r 1}} \qquad (3)$$

where the subscripts 1 and 2 refer to the two rates.

Materials and Processing

Twelve different groups of lumber were obtained from eleven plastic lumber manufacturers from around the country. The composition of the products varied greatly: some materials were mixed plastics of different percentages, some were pure resins, others contained fillers such as wood pulp or fiberglass, but all products were constituted principally of recycled polyethylenes. There were visible differences among the different profiles: some were foamed, some had extremely large voids, and one group was hollow. The authors chose four participants as representative of the twelve groups of lumber for this report, identified as B,D, F, and L. Morphological differences will be highlighted by scanning electron microscopy (SEM).

Experimental Procedure

Compressive tests were based on ASTM D695-91, modified for recycled plastic lumber. As noted in previous work, the ASTM sample size is modified to allow for larger cross-sections.[1] The ASTM procedure was also modified for actuator speed to obtain the two strain rates for this study.

In order to obtain a relation for the slope of log ε vs log t, mechanical tests at two strain rates are required: 0.0083%/min and 0.83%/min, rates which correspond to actuator rates of 0.00254 cm/min (0.001 in/min) and 0.254 cm/min (0.1 in/min), respectively. At each strain rate, five samples were tested from each group.

Creep measurements in compression were made using two levels of stress, representing 20 and 40% of a given material's yield strength as determined from ramped tests run at a strain rate of 0.83%/min. These incremental percentages were chosen so as to compare the relation of applied stress to creep strain for each of the four materials. Therefore, samples from company B were subjected to stress levels of 1.90 MPa, and 3.81 MPa; company D to 2.30 MPa and 4.60 MPa; company F to 2.86 MPa and 5.72 MPa; and company L to 2.36 MPa and 4.72 MPa. Each creep stress was fully applied within ten seconds. Once fully applied, the stresses were held constant for periods of 100 and 20 hours for values of stress equal to 20 and 40% of the yield point, respectively. Two samples from each company were tested for each stress level.

For the SEM study, pieces approximately 5 x 5 x 10 mm, were cut from the dense outer surfaces of the profiles. These were notched and then fractured at the temperature of liquid nitrogen. Notches were placed in order to obtain two different orientations, parallel and perpendicular to the long axis of each of the bulky profiles (the direction of flow). Fractured surfaces were mounted on aluminum stubs, gold-coated, and examined using a Hitachi S-2700 SEM operating at 15-20 keV.

Results

Table 1 shows a comparison of observed values of creep strain with values calculated from ramped data: for a given company, stress, and strain rate, the results show good agreement, differing on average by only 10.3%; for a given company and stress, calculated values of the creep exponent n_c differ from experiment on average by only 13.5%.

For the 20% stress levels, material L possesses by far the smallest value of n_c, less than half of that for the other three samples, indicating its superior resistance to creep. For each material, an increase in applied stress by a factor of two results not only in increased strain for a given time, but produces increased values of n_c, i.e., as high as 90% for materials F and L, and by 38% for B and D.

Also of interest is a comparison of values of creep moduli (not shown here), $E = (\sigma_c/\varepsilon_c)$, which differed considerably between companies, i.e., by as much as 63% between L and D at 20% yield stress, and by 65% at 40% yield stress.

The observed morphologies for these four materials were found to be diverse and complex. Materials D and F each appear to be constituted principally of two polymeric components, the more abundant phase in each case being HDPE. Material D, initially reported to be homogeneous,[2] was found at high magnification to contain an entangled, oriented, two-phase system (Figure 5), while material F appears constituted of a more loosely bound, oriented, two-phase system (Figure 6). Finally, material L was found to contain a non-uniform distribution of glass fibers, ranging in volume percent on average from 5-15%. In addition, material L was found to contain numerous voids (Figure 7), as well as a small volume percentage of impurities in the form of particulate dispersions.

Conclusion and Future Work

Creep properties such as strain and modulus can be estimated from ramped tests performed over a relatively short period of time. Morphology plays a key role in resisting the tendency to creep. For example, material L has superior resistance due to the presence of oriented glass fibers. Other two-phase systems, which contain polymeric constituents alone, do not fare as well in resisting creep. We note that at 40% of the yield stress, material L behaves more like the others, an indication that this level of stress exceeds the limit of the effective interaction between the HDPE matrix and the glass fibers.

While this study confirms that it is possible to obtain a good estimate of creep behavior for a period of time on the order of one hundred hours, it is necessary to develop a theoretical treatment that will predict creep properties over a much longer period of time, say, 25 years. To do this directly from ramped data, it would be necessary to run a ramped test at an extremely small strain rate over a 25-year period. As this is unacceptable, the only alternative is to develop a model that is capable of calculating long-time ramps from short-time ramps. The precedent for this effort can be seen in an existing semi-empirical model that uses a scaling technique to predict stress-strain curves at different strain rates for virgin polymers loaded in tension.[3] At this time the authors are making one effort to see if this model is applicable to commingled plastic materials loaded in compression, while at the same time making another effort to either modify the scaling model or develop an entirely new approach. A successful model will prove useful in predicting both the long and short-term mechanical behavior of commingled plastic materials, thereby moving the recycled plastic lumber industry in the important direction of establishing standardized test methods and lumber grades for use in construction applications.

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Key Words: creep properties, plastic lumber, plastics recycling, polyolefinic composites

		Strain rate equals 0.0083 (m/m)/min			Strain rate equals 0.000083 (m/m)/min				
Company	**σ_c MPa**	**t_r min**	**ε_c (m/m) Calculated**	**ε_c(m/m) Observed**	**t_r min**	**ε_c (m/m) Calculated**	**ε_c (m/m) Observed**	**n_c Calculated**	**n_c Observed**
B	1.90	1.18	0.0053+/- 0.0004	0.0046+/- 0.0003	177.1	0.0079+/- 0.0007	0.0073+/- 0.0005	0.080	0.092
	3.81	2.67	0.0126+/- 0.0013	0.0100+/- 0.0007	486.3	0.0229+/- 0.0024	0.0194+/- 0.0012	0.136	0.127
D	2.30	1.19	0.0054+/- 0.0006	0.0061+/- 0.0005	189.8	0.0094+/- 0.0005	0.0094+/- 0.0004	0.094	0.087
	4.60	2.75	0.0128+/- 0.0014	0.0151+/- 0.0012	524.6	0.0245+/- 0.0017	0.0283+/- 0.0011	0.125	0.120
F	2.86	0.95	0.0044+/- 0.0004	0.0052+/- 0.0005	161.2	0.0074+/- 0.0011	0.0077+/- 0.0009	0.100	0.077
	5.72	2.10	0.0100+/- 0.0013	0.0091+/- 0.0009	461.0	0.0219+/- 0.0045	0.0201+/- 0.0023	0.146	0.147
L	2.36	0.41	0.0018+/- 0.0001	0.0019+/- 0.0001	46.8	0.0020+/- 0.0001	0.0023+/- 0.0001	0.028	0.042
	4.72	0.86	0.0038+/- 0.0002	0.0038+/- 0.0001	121.6	0.0054+/- 0.0003	0.0056+/- 0.0002	0.070	0.080

Table 1: Calculated and Observed Values of Creep Strain. σ_c = creep stress; t_r = ramped time such that average ramped stress equals σ_c; ε_c = creep strain; n_c = creep exponent.

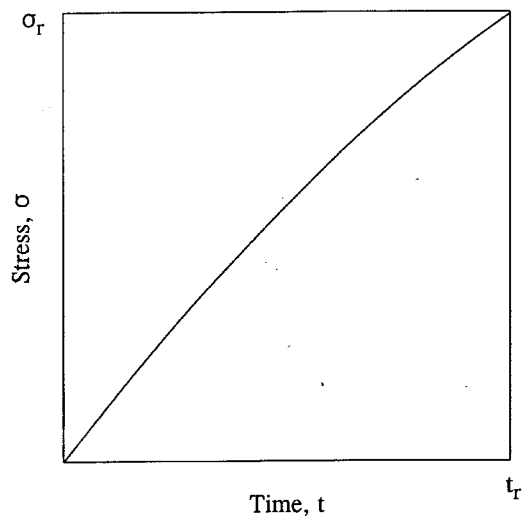

Figure 1a

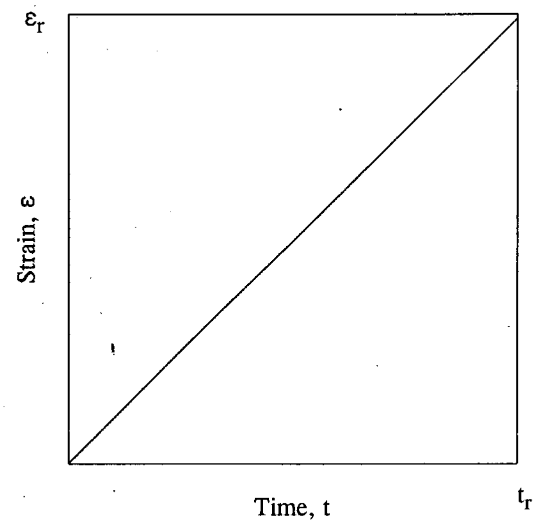

Figure 1b

Figures 1a and 1b: Ramped stress vs time and ramped strain vs time, respectively. When $t = t_r$, $\sigma = \sigma_r$, and $\varepsilon = \varepsilon_r$.

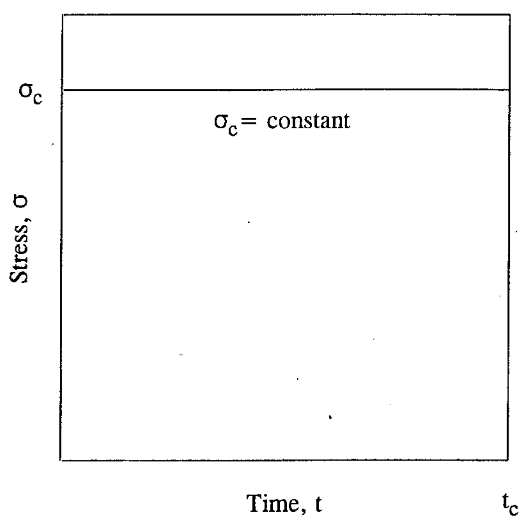

Figure 2a

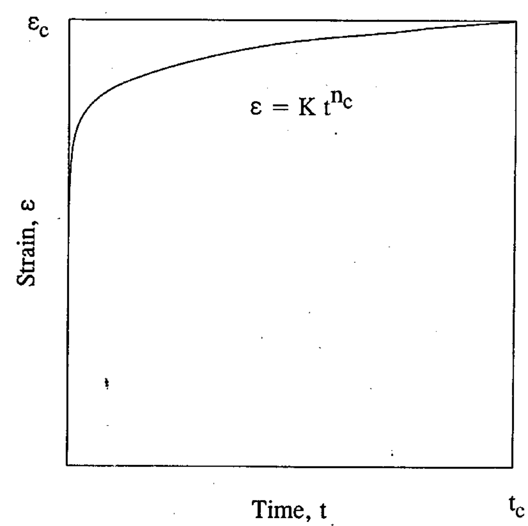

Figure 2b

Figures 2a and 2b: Stress vs time and strain vs time, respectively, for creep test. σ_c = constant, and when $t = t_c$, $\varepsilon = \varepsilon_c = K(t_c)^{nc}$, where K is a constant and n_c is the creep exponent.

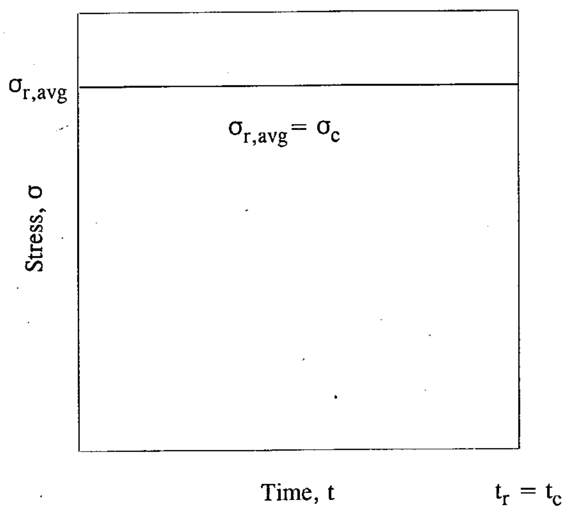

Figure 3a

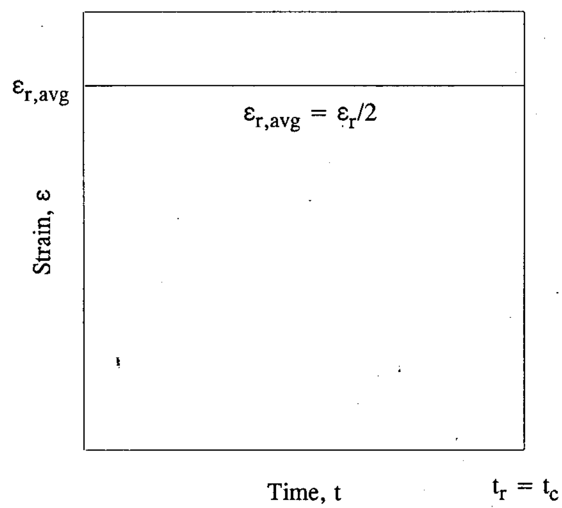

Figure 3b

Figures 3a and 3b: Average stress vs time and average strain vs time, respectively, for ramped test. Figure 3a is identical in form to Figure 2a: $\sigma_{r,avg} = \sigma_c$.

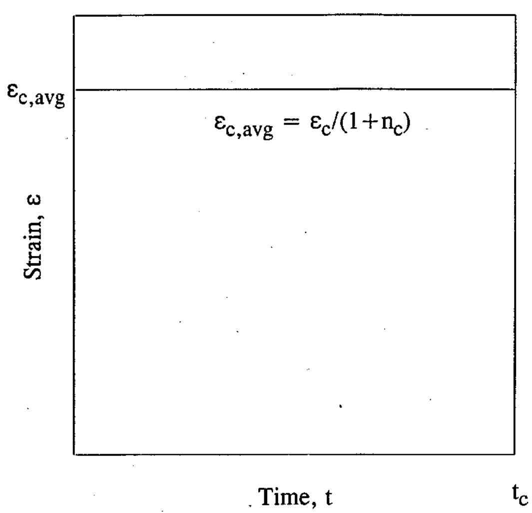

Figure 4a

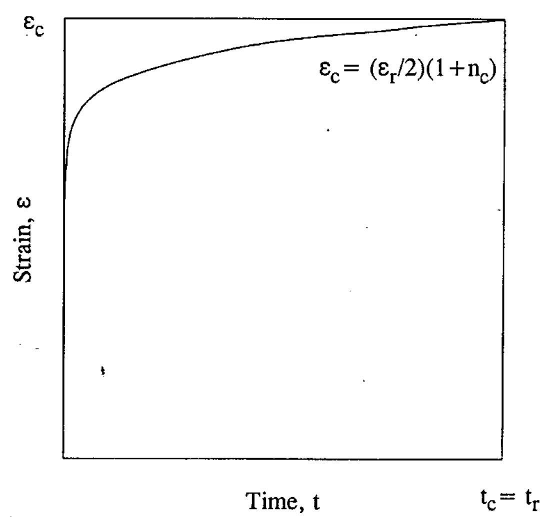

Figure 4b

Figure 4a: Average creep strain as a function of the creep exponent n_c.
Figure 4b: Relation between creep strain and ramped strain.

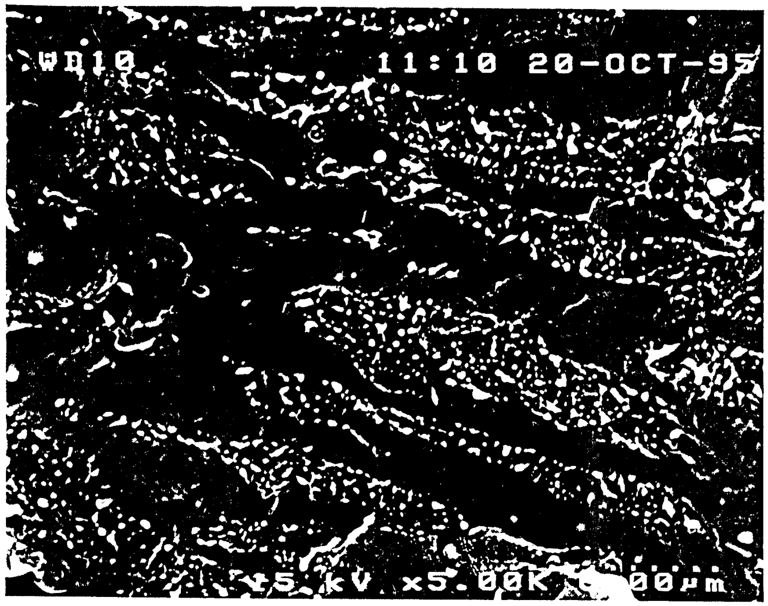

Figure 5: Scanning electron micrograph of material D, showing the entanglement and orientation of a two-phase system. The phases can be identified by either the smooth or rough topography. The surface is parallel to the long axis of the lumber profile, running across the width of the photo.

Figure 6: Scanning electron micrograph of material F. A highly oriented two-phase system is evident. The surface is parallel to the long axis of the lumber profile, running across the width of the photo.

Figure 7: Scanning electron micrograph of material L, showing a 'log-jam" of oriented glass fibers in a porous polymeric matrix. The surface is parallel to the long axis of the lumber profile, running across the width of the photo.

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