Long-Term Creep Of Commercially Produced Plastic Lumber

Kenneth E. Van Ness, Ph.D., Washington and Lee University
Thomas.l: Nosker, Ph.D., Rutgers University
Richard w: Renfree, Ph.D., Rutgers University
Jeffrey R. Killion, Washington and Lee University

Abstract

Samples of lumber manufactured from recycled plastics by four different companies were subjected to stress-strain tests at two rates of strain over relatively short intervals of time. A simple model uses data from the strain-rate tests to calculate long-term (-25 years) creep strain. Calculated long-term values range from approximately 25-80% greater than values extrapolated from short-term data. Results for the recycled products are compared with experimental creep data for virgin polyethylene. The findings are examined in terms of morphological features and sample composition.

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, which vary widely from company to company, though the products have similar appearance.[i] An area which 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 outlined a theory to calculate short- term (up to several hours) creep strain from stress-strain tests carried out at two rates of strain, one being 100 times the other.[ii] Calculated values of creep strain were in good agreement with experimental values for the four types of plastic lumber tested. The current study outlines a theory to predict long-term (- 25 years) creep behavior for these same selected groups of lumber.

A semi-empirical model is formulated and used to predict creep strain from the same stress-strain data used in the previously mentioned short-term study. Calculated values of creep strain were found to be approximately 20-80% greater than values extrapolated from short-term data. The results were compared with long-term creep data available from a 26-year study of virgin polyethylene.[iii] Findings suggest that this predictive method may 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.

Earlier Results

Previously,[2] a method was used to equate effectively the average strain obtained during a strain-ramped test, in which some average stress is sustained over a time interval t, to the creep strain obtained during a true creep test carried out at a creep stress equal to the average stress mentioned above and held over the same interval t. Therefore, in principle, each point on a true creep-strain-versus-time curve is related directly to a ramped-strain test performed over a time interval t, such that the average stress, $\bar{\sigma}$, sustained during the ramped test is equal to the creep stress, σ_c, or

$$\bar{\sigma} = \sigma_c = \frac{\int_0^t \sigma(t)dt}{\int_0^t dt} \tag{1}$$

For example, to estimate 25-year creep strain from ramped data would require a 25-year ramp, a test that is equally as impractical as a 25-year creep experiment. However, a simple model predicts a long-term ramp from two experimental short-term strain-ramps, carried out over time intervals ranging from 10 minutes to 10 hours and where one strain-rate is 100 times the other.

Predictive Theory

The fundamental problem is to find a relation between values of stress and strain for different strain rates. The starting point of the theory is based upon a heuristic argument, namely, that for any two strain-ramped tests, an exponential relation exists between the ratio of the strain- rates and any two states of equal strain-energy density for the corresponding stress-strain curves. Consider two strain-ramps given by rates of $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$, and where the strain-energy densities are given by the products $\sigma_1\varepsilon_1$ and $\sigma_2\varepsilon_2$ for the two curves, 1 and 2. We take

$$\left[\frac{\dot{\varepsilon}_1}{\dot{\varepsilon}_2}\right]^n = \frac{\sigma_1}{\sigma_2} = \frac{\varepsilon_2}{\varepsilon_1} \tag{2}$$

where n is a fraction less than one, and where $\sigma_1\varepsilon_1 = \sigma_2\varepsilon_2$. While the general form of equation has been used before,[iv] our usage here is quite different.

The exponent n in equation (2) is found by fitting experimental stress-strain data between two strain-ramped curves over the full range of $\sigma\varepsilon$ values, the upper limit of which must be less than the failure point. The ratio $\dot{\varepsilon}_1/\dot{\varepsilon}_2$ is, in this work, 100. The resulting plot of n versus $\sigma\varepsilon$ can be fit typically by a fifth order polynomial. Knowing $n = n(\sigma\varepsilon)$, one can calculate stress-strain relations for any strain-ramp relative to one of the two known experimental ramps, simply by applying equation (2). More specifically, if the subscript r denotes known reference values and the subscript i stands for the calculated values, we have

$$\sigma_i = \sigma_r \left[\frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_r}\right]^{n(\sigma_r\varepsilon_r)} \tag{3}$$

and

$$t_i = \frac{\sigma_r\varepsilon_r}{\sigma_i} \Big/ \dot{\varepsilon}_i \tag{4}$$

The plot of σ_i versus t_i can be fit by a polynomial. The connection of $\sigma_i = \sigma(t_i)$ to the determination of the creep strain ε_c at a time t for a creep stress σ_c is that the average value of stress over the stress-time curve must be equal to σ_c. Therefore, the problem is to determine the value of the strain rate $\dot{\varepsilon}_i$ which results in the relation $\sigma_i = \sigma(t_i)$ that uniquely satisfies equation (1). This can be accomplished by solving equations (1) and (3) simultaneously for the unknowns $\dot{\varepsilon}_i$ and t_r. Unfortunately, the form of $\sigma_i = \sigma(t_i)$ is, in general, not known, making this exercise mathematically intractable. However, a simple approximation gives an excellent first-order estimate of $\dot{\varepsilon}_i$, which can easily be improved to give an exact solution.

The approximation is based upon the assumption that if equation (3) holds for each and every paired value of strain energy density, $\sigma_i\varepsilon_i = \sigma_r\varepsilon_r$, that the same relation will apply to the average values of strain energy density for the two ramped curves, or, when $\overline{\sigma}_i\overline{\varepsilon}_i = \overline{\sigma}_r\overline{\varepsilon}_r$. The average creep strains are then given by $\overline{\varepsilon}_i = \dot{\varepsilon}_i t_i/2$ and $\overline{\varepsilon}_r = \dot{\varepsilon}_r t_r/2$, or

$$\overline{\sigma}_i\dot{\varepsilon}_i t_i = \overline{\sigma}_r\dot{\varepsilon}_r t_r \qquad (5)$$

where t_i is a known creep time, $\dot{\varepsilon}_r$ is given, and $\overline{\sigma}_r$ is calculable from the known relation $\sigma_r = \sigma(t_r)$ and equation (1).

Equation (3) may be written in terms of average quantities, or

$$\overline{\sigma}_i = \overline{\sigma}_r\left[\frac{\dot{\varepsilon}_i}{\dot{\varepsilon}_r}\right]^{\overline{n}} \qquad (6)$$

where $\overline{n} = n(\overline{\sigma}_i\overline{\varepsilon}_i) = n(\overline{\sigma}_i\,\dot{\varepsilon}_i t_i/2)$. Equations (5) and (6) can be solved simultaneously to find $\dot{\varepsilon}_i$ and t_r which is not used further. The creep strain over the interval of time t_i is given by $\overline{\varepsilon}_i = \dot{\varepsilon}_i t_i/2$.

Materials and Processing

The four groups of plastic lumber used for this study were manufactured by four different companies. Identified as materials B, D, F, and L, their morphological characteristics and mechanical properties have been described in detail elsewhere.[1,2] The composition of the products varied greatly: some contained blends of polyolefins, one contained glass fibers, but all were constituted principally of recycled polyethylenes.

Experimental Procedure

Compressive tests were based on ASTM D695-91, modified for recycled plastic lumber. The ASTM sample size was modified to allow for larger cross-sections, and the ASTM procedure was also modified for actuator speed to obtain the two strain rates for this study.

The materials were tested at two strain rates, 0.0083 %/min and 0.83 %/min. Based upon the ramped tests run at 0.83%/min, a creep stress level of 20 % of a given material's yield stress was selected for each material to study the long-term creep behavior. Therefore, samples from company B, D, F, and L were analyzed for creep stresses of 1.9, 2.3, 2.86, and 2.36 MPa, respectively.

Results

For comparative purposes, a 26-year experimental creep study by Findley of virgin low-density polyethylene[3] will be examined along with the calculated creep strain over a similar 26-year period for each of the four recycled materials. It is well known that long-term creep strain may be significantly higher than that calculated from an extrapolation of the short-term rate of increase in creep strain with time. Figure 1 shows the results of the Findley study: experimental strain versus time for virgin polyethylene is increasingly greater than values of strain calculated from the early part of the creep curve. To extrapolate from early data, it is useful to define, as a measure of the change of strain with time, the creep exponent, n_c, which, between any two points, 1 and 2, on a creep curve, is given by

$$n_c = \frac{\log\left(\varepsilon_{r2} / \varepsilon_{r1} \right)}{\log\left(t_{r2} / t_{r1} \right)} \tag{7}$$

For the virgin material and using the strain at 16 hours as state 1, the creep exponent increases by 60%, from 0.045 at 16 hours to 0.072 at 26 years, and the measured creep strain at 26 years is 30% greater than the value calculated using the short-term creep exponent.

Figures 2-5 show similarly the results for the recycled materials, and Table 1 gives a more detailed presentation of the creep values for the four materials. The change in the creep exponent n_c over the 26-year period ranges from 24.5 % for material D to 54 % for material F, with an average of 39.4 %; 26-year strain values calculated using equations (5) and (6) differ from values extrapolated from the early part of the creep curve by from 17.9 % for material L to 82.4 % for material F, with an average of 42.8 %. The trend in these percentage differences is in good agreement with the 26-year creep data for virgin polyethylene.

Of the four materials, L, which contains oriented glass fibers, is clearly the most creep resistant over time. Material F, which was found to have the highest yield stress of the lot, was the least creep resistant, most likely due to its loosely bound two-phase polyolefinic microstructure. In contrast, material D, which consisted of an entangled, oriented two-phase polyolefin blend, did not change as much over time.

Conclusion

Long-term creep strain can be estimated from strain-ramped tests performed over a relatively short period of time (from 10 minutes to 10 hours). Morphology plays a key role in resisting the tendency to creep. For example, materials containing oriented glass fibers are capable of offering superior resistance to creep. Two-phase systems which contain polyolefinic constituents alone, do not appear to fare as well in resisting creep, with the more loosely bound systems creeping the most.

These findings suggest that a simple semi-empirical method may be used to estimate long-term mechanical properties from short-term tests. thereby facilitating the design of plastic lumber for load-bearing applications.

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Key Words: creep properties. plastic lumber, plastics recycling. po1yolefinic composites

Table 1: Calculated and Extrapolated Values of Creep Strain and Creep Exponent.

t = creep time in hours; n_c = creep exponent; σ = creep stress, MPa; ε = creep strain, m/m.

Δn_c, $\Delta\varepsilon$ = % difference for theory relative to short-term extrapolated values.

Company (σ, MPa)	t(hr)	n_c	ε (m/m) Calculated	ε (m/m) Extrapolated	Δn_c, %	$\Delta\varepsilon$, %
B (1.9)	2.95	0.080	0.0079	0.0079	----	----
	227760	0.112	0.0273	0.0194	40.0	40.7
D (2.3)	3.16	0.094	0.0086	0.0086	----	----
	227760	0.117	0.0320	0.0246	24.5	30.1
F (2.86)	2.69	0.100	0.0074	0.0074	----	----
	227760	0.154	0.0425	0.0223	54.0	82.4
L (2.36)	0.78	0.028	0.0020	0.0020	----	----
	227760	0.039	0.0033	0.0028	39.2	17.9

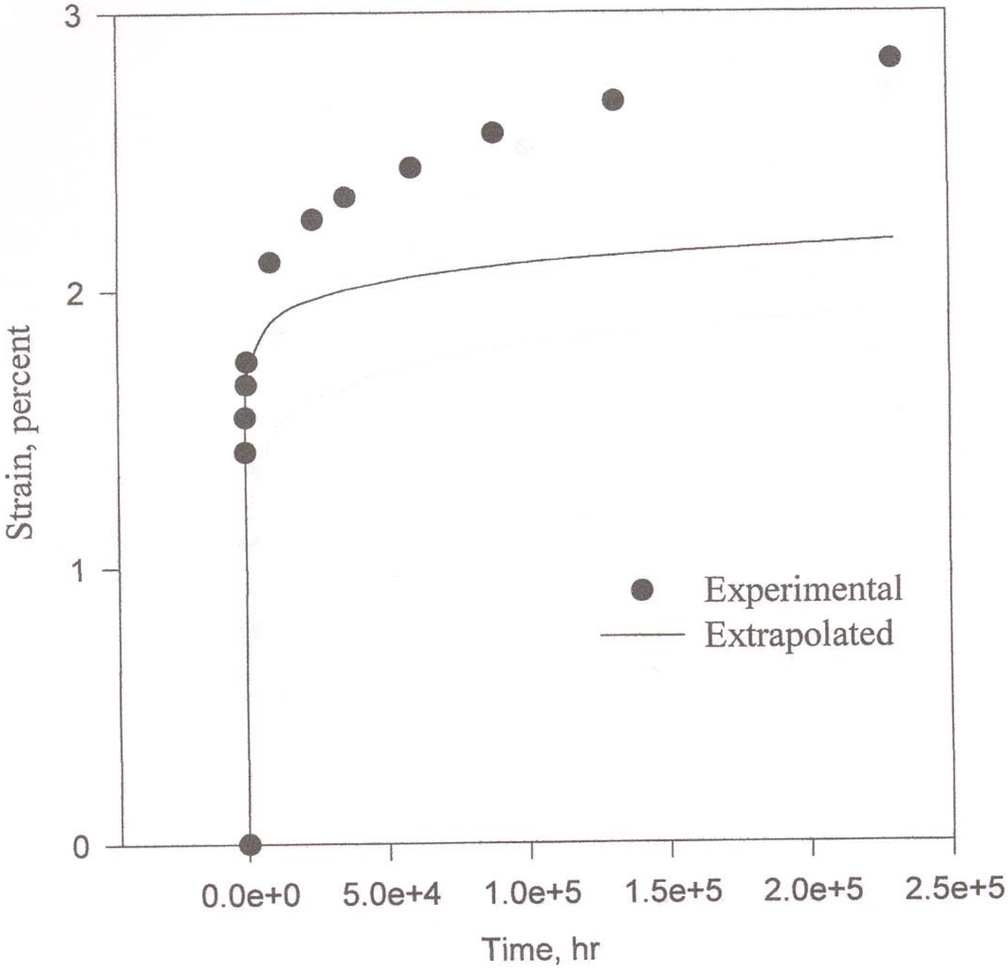

Figure 1: Experimental creep strain and extrapolated creep strain for virgin polyethylene.[3]

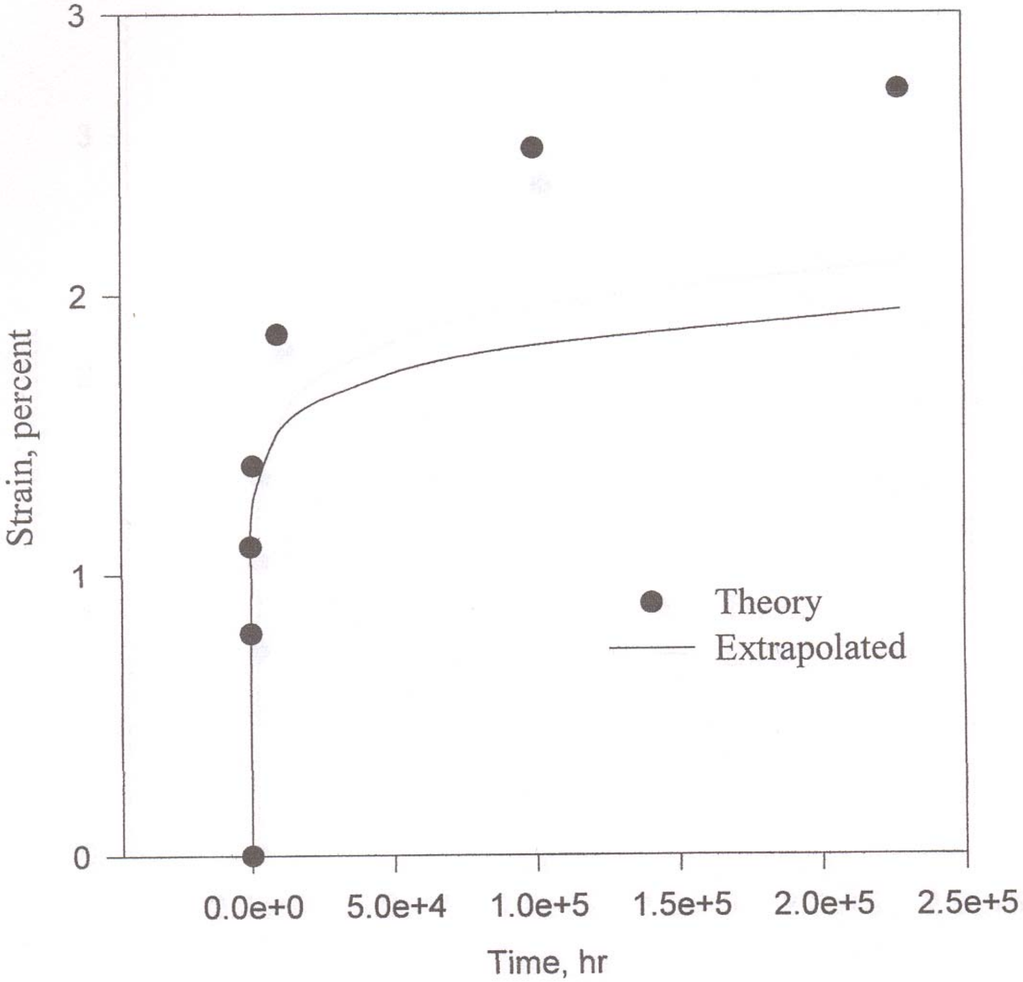

Figure 2: Calculated, theoretical creep strain and extrapolated creep strain for plastic lumber company B.

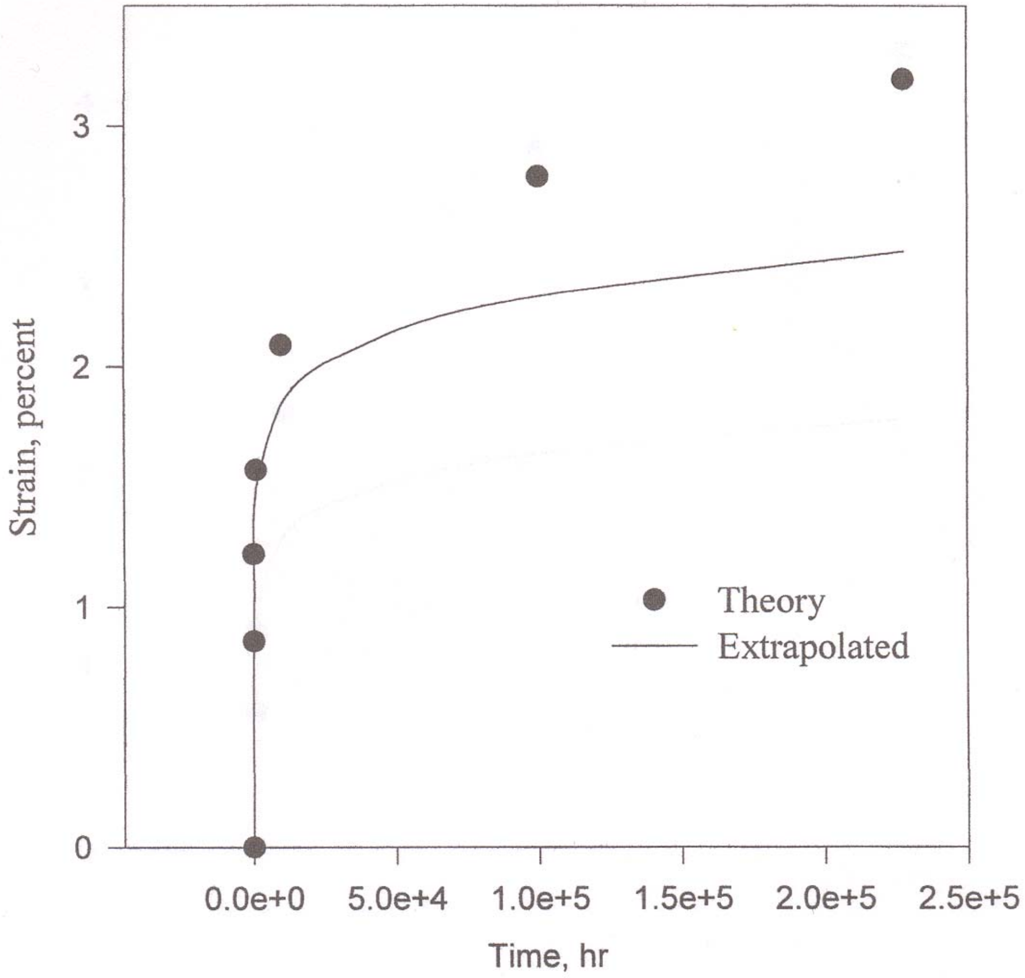

Figure 3: Calculated, theoretical creep strain and extrapolated creep strain for plastic lumber company D.

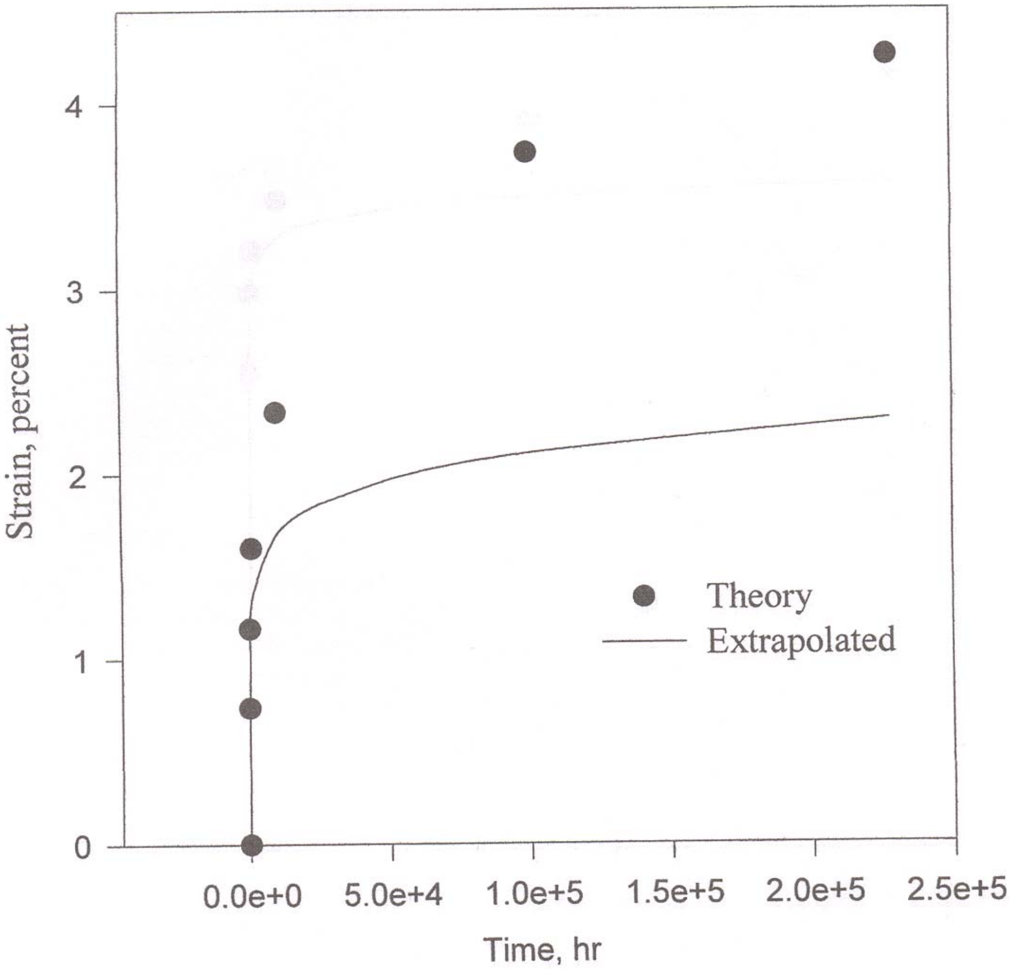

Figure 4: Calculated, theoretical creep strain and extrapolated creep strain for plastic lumber company F.

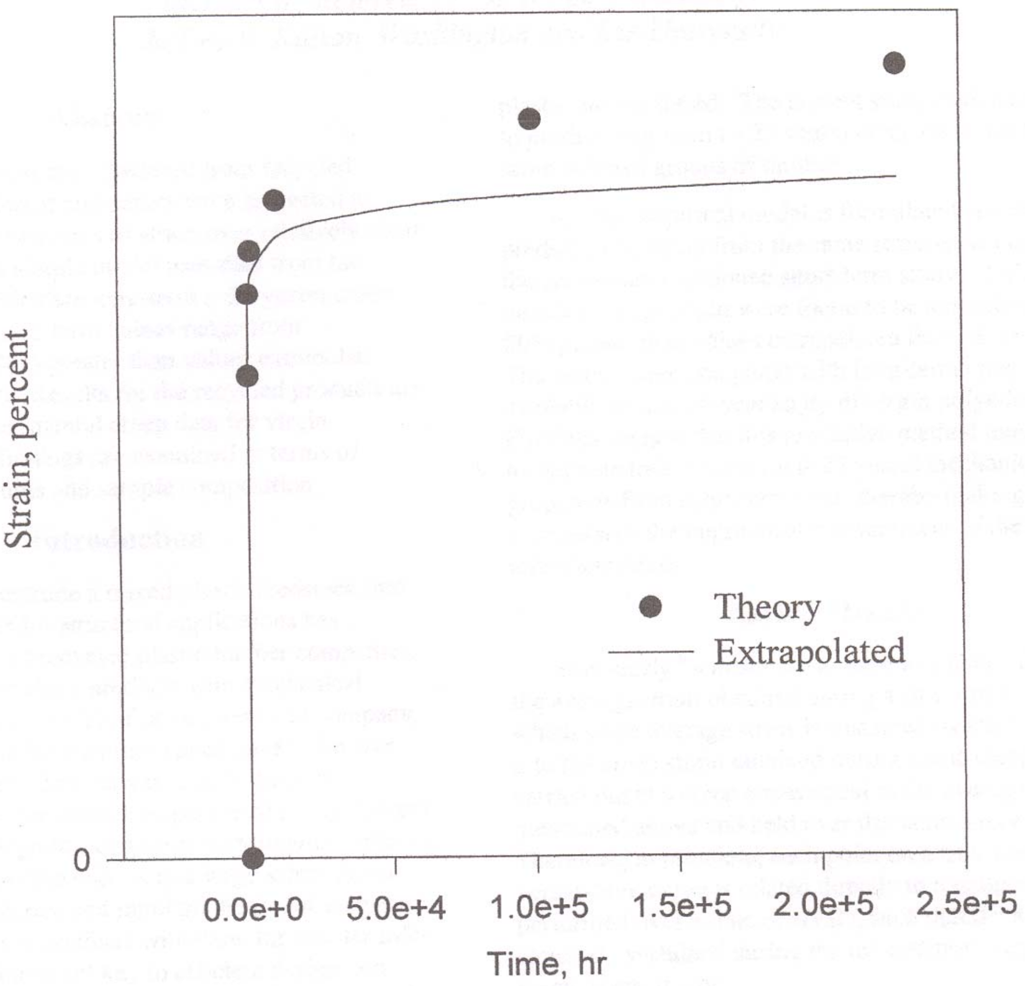

Figure 5: Calculated, theoretical creep strain and extrapolated creep strain for plastic lumber company L.

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