PREDICTING FLEXURAL CREEP IN PARTICLEBOARD[1]

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ABSTRACT

An analytical expression that relates flexural creep behavior to time, temperature, and stress was used in this study to predict the long-time performance of a commercial particleboard from the short-time behavior exhibited in a conventional static bending test. The particleboard exhibited a hyperbolic deflection—log time relationship under all conditions studied while deflection predicted from tests at elevated temperature was nearly linear with log of time. Both Larson-Miller and Goldfein parameters provide reasonable estimates at low stress levels. At higher stress levels, the Larson-Miller parameter provides more conservative estimates of the behavior in the 1000–3000 hr range. Neither method predicts accurately the increasing creep rates at the high stress levels and longer times.

Particleboard is a viscoelastic material which responds both elastically and plastically when subjected to stress. The factor of time plays a more important role in the behavior of particleboard than in solid wood stressed parallel to the grain.

The purpose of this study was to determine experimentally the short-time behavior of one commercial particleboard at high temperature and from these data to predict the long-time performance by use of both Larson-Miller and Goldfein parameters described below. The long-time behavior was experimentally determined and compared with the predicted behavior.

Bryan (1960) investigated the bending strength of particleboard under long-time loading. His regression lines suggested that a decrease of only 2 to 4% in flexural stress, in a range from 65 to 80% of nominal modulus of rupture, brought about a tenfold increase in time to failure. Bryan and Schniewind (1965) investigated the effects of moisture changes on the deflection of flexurally loaded particleboard. Both adsorption and desorption increased relative creep in particleboard under long-term flexural loading.

Commercial particleboard and hardboard were observed at C.S.I.R.O. (1967, 1968) during successive cycles of moisture content while under flexural load, and the effects were compared with those observed in solid wood. The fact was confirmed that the behavior in particleboard was qualitatively similar to that in solid wood. Haygreen and Sauer (1969) studied the prediction of flexural creep in hardboard by the use of a time-temperature relationship. They showed that the time-temperature relationship developed by Goldfein could be used to predict creep and stress rupture in hardboard under load levels and moisture contents that produced nonlinear viscoelastic behavior.

Numerous approaches to the prediction of creep have been taken with other materials. Linear viscoelastic methods are often used to predict creep and stress relaxation in materials that are linearly viscoelastic. Material is linearly viscoelastic if, when it is stressed below some limiting stress, small strains are at any time almost linearly proportional to the imposed stress. Linear behavior often does not persist throughout the time span which is of concern. Linear viscoelastic theory is not valid in nonlinear regions, but prediction methods based upon rate theory may be used in such cases.

One application of rate thory is the Larson-Miller (1952) parameter:

$$K = T\ (C + \log\ t) \qquad (1)$$

where T is the absolute temperature, t is the time, and C is the material constant. This equation was used by Hollomon and Jaffe (1945) to express the relation between

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tempering time and temperature for a given hardness of steel. They found that as long as the parameter K had a constant value, the same hardness was produced with a short tempering time and a high temperature as with a long tempering time and a low temperature. This equation has since been used to predict creep and stress rupture in steels and other alloys. Larson and Miller suggested a value of 20 for C, but other investigators found that the use of the parameter was improved by experimentally establishing C for the specific material in question.

The Larson-Miller parameter has also been applied to plastics. Carey and Oskin (1956) found that for some materials of fiberglass-reinforced polyester a family of Larson-Miller curves obtained for each temperature tended to coincide at low values of K and diverge at higher values. Gloor (1958) used the parameter with two other rate processes to predict the stress rupture of high density polyethlene. He found values of C equal to 21 and 47.5 for brittle failure and ductile failure, respectively.

An alternate method of predicting creep was developed by Goldfein (1960) for plastics. Goldfein (1954) first used the Larson-Miller parameter but later he modified it to:

$$K = \frac{T\,T_o}{T_o - T}\ (20 + \log t), \qquad (2)$$

where T is the absolute temperature of the process in degrees Rankine, T_o is the absolute temperature at which the material has no strength, t is the time in hours.

The practical utility of Eq. (1) and (2) is that knowing the temperatures involved, the deflection or time to rupture can be predicted over long periods using data from short-term tests. Goldfein (1960) provides a detailed explanation of the procedure for predicting creep and time to failure. The deformation observed in a short-term bending test at an elevated temperature is related to the deformation that takes place at a lower temperature over a longer period of time. The short-term data obtained can thus be used to estimate long-term tangent modulus data through the development of a master modulus curve.

Since the time t is theoretically the time under constant load, a steady load time equivalent ($SLTE$) must be used in the development of a master modulus curve for tests conducted under increasing load. Goldfein has used 10^{-3}, 10^{-4} and 10^{-5} hours as the $SLTE$ in static bending tests. If T_o is known, a K value may then be computed for each temperature level tested. A master modulus curve may then be constructed by plotting the modulus vs. K for each temperature tested. Once the master curves have been established, it is possible to predict the deflection at any time. To do this the modulus corresponding to the K value of any time and temperature combination is determined. The predicted deflection is obtained by using the modulus in the same way that the modulus of elasticity is used in elastic stress analysis.

EXPERIMENTAL PROCEDURE

The specimens used in this study were selected from two panels of commercial three layer particleboard produced from Douglas-fir bonded with phenolic resin. The thickness was ⅜ inch and the density was 40.5 pounds per cubic foot. The boards were cut into 14- by 14-inch squares. The side-matched squares were divided into two samples. One sample was conditioned for one month in a controlled-environment room held at a temperature of 70 F and a relative humidity of 50% for low moisture content. The other sample was conditioned at a temperature of 70 F and at relative humidity of 80% for high moisture content. The squares were then cut into 2- by 14-inch bending specimens. Seven groups of twelve specimens each were randomly selected for each moisture content level. Four of these groups were used in short-time bending tests for the four temperature levels, 32, 72, 120, and 160 F. The other three groups were used in the long-term creep tests at the three stress levels of 252, 755 and 1258 psi. All bending tests, both short-term static and long-term creep, were carried out with midspan loading on a span of 12 inches.

TABLE 1. *Results of static bending tests at four temperature levels and two moisture contents*

Nominal temperature °F	Actual temperature °F	Moisture content %	Modulus of rupture psi		Deflection at failure (inch)		Tangent modulus (10^5 psi)					
							at 252 psi		at 755 psi		at 1258 psi	
			Mean	C.V.	Mean	C.V.	Mean	C.V.	Mean	C.V.	Mean	C.V.
			LOW MOISTURE CONTENT									
32	23.1	7.31	3002	10.22	0.301	8.73	7.491	7.50	7.43	7.96	7.32	8.98
72	73.4	7.43	2635	11.14	0.353	8.07	5.65	9.21	5.59	9.19	5.43	8.72
120	118.6	7.41	2352	9.52	0.396	8.21	4.70	8.78	4.58	9.56	4.25	12.04
160	160.0	7.33	2243	11.63	0.425	5.71	4.31	11.87	4.24	10.15	3.82	13.04
			HIGH MOISTURE CONTENT									
32	33.8	10.16	2737	12.65	0.326	11.68	6.54	6.34	6.29	7.52	5.88	9.05
72	75.2	10.13	2183	15.31	0.365	8.54	4.86	6.52	4.70	7.69	4.22	10.81
120	122.0	10.19	1951	8.96	0.466	9.76	3.79	6.96	3.40	6.81	2.77	10.26
160	162.3	10.16	1703	7.98	0.497	7.88	3.26	6.06	2.76	7.67	2.11	11.89

Remarks: C. V. is the coefficient of variation (standard deviation expressed as a percentage of the mean).

The static bending tests were conducted on a universal testing machine with a load vs. deflection recorder. The head speed was 0.5 inch per minute. A heating and cooling chamber was built around the testing jig to maintain specimen temperature during tests. A dummy sample with thermocouple was used to determine the actual test temperature. Nominal temperatures at test were 32, 72, 120 and 160 F. The moisture content of specimens equilibrated at 70 F and 50% RH and at 70 F and 80% RH were 7.3% (low MC) and 10.1% (high MC), respectively. After being weighed and measured in width and thickness to the nearest 0.001 inch, all specimens were wrapped in aluminum foil to reduce moisture change during testing. The actual moisture content was measured after testing. It was found that by using this procedure it was possible to maintain the temperature and moisture content very near the nominal levels.

The long-term creep tests were carried out in a controlled environment room at 70 F and relative humidities of 50 and 80%. The moisture content of the specimens was essentially the same as during static tests. Three stress levels, 252, 755 and 1258 psi, were used at each moisture level. The stress levels were nominal 10, 30 and 50% of the average static modulus of rupture of the board at low moisture content. Flexural stress was computed assuming that the simple elastic stress distribution in flexure exists. The measurement of deflection was made with a dial gage. Before the tests were started, each sample was randomly assigned to a load level. Twelve specimens were tested at each combination of moisture content and stress level. The tests were continued for 3600 hr and 3000 hr for the low and high moisture content level respectively.

RESULTS AND DISCUSSION

The results of the static bending tests are shown in Table 1. Tangent modulus values were determined at stress levels corresponding to those used in the long-term tests. A tangent modulus is the slope of a line tangent to the stress-strain curve at a given stress. In Fig. 1 is shown the effect of temperature on both modulus of rupture and deflection at failure of particleboard. The board at high moisture content was affected to a greater extent by temperature than that at low moisture content. The linear relationships between modulus of rupture and deflection at failure and temperature are as follows:

$$R_1 = 3.09 \times 10^3 - 5.7\,T \quad (3)$$
$$R_2 = 2.89 \times 10^3 - 7.6\,T \quad (4)$$
$$D_1 = 0.283 + (9.13\,T \times 10^{-4}) \quad (5)$$
$$D_2 = 0.275 + (14.00\,T \times 10^{-4}) \quad (6)$$

where

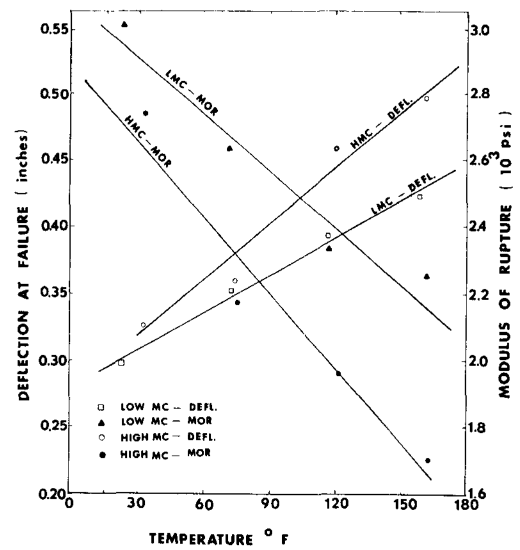

FIG. 1. The relationships between deflection at failure, modulus of rupture, and temperature for particleboard at both low moisture content (LMC) and high moisture content (HMC), plotted from data of Table 1.

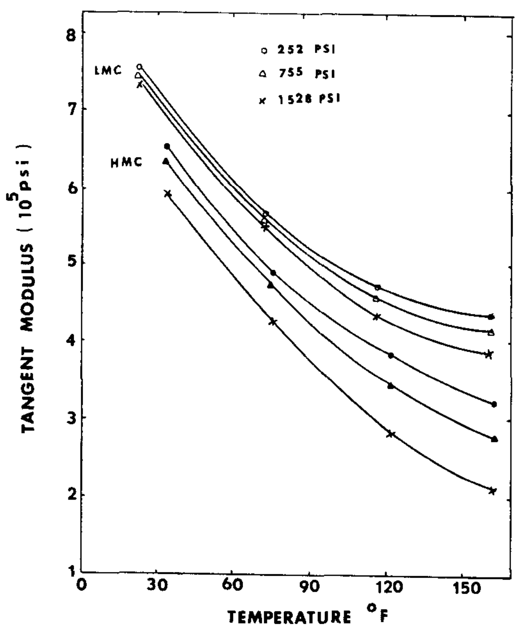

FIG. 2. The relationship between tangent modulus and temperature at both low moisture content (LMC) and high moisture content (HMC), plotted from data of Table 1.

R_1 = the modulus of rupture at low moisture content, (psi)
R_2 = the modulus of rupture at high moisture content, (psi)
D_1 = the deflection at failure at low moisture content, (inches)
D_2 = the deflection at failure at high moisture content, (inches)
T = temperature °F

Since the load-deflection curves in particleboard often have a limited linear portion, the use of a flexural modulus of elasticity is quite restricted. Tangent modulus values for predicting creep were determined from the load-deflection curves at three flexural stress levels, 252, 755 and 1258 psi. The relationships between tangent modulus and temperature are shown in Fig. 2. As would be expected, the particleboard deformed more plastically at the high temperature

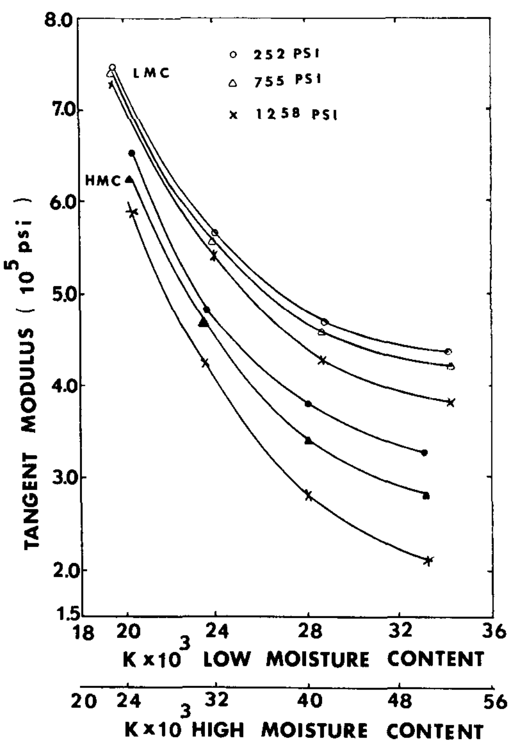

FIG. 3. Master modulus curves using Goldfein parameter $K = T_o\,T\,(24 + \log t)/(T_o - T)$ for particleboard at both low moisture content (LMC) and high moisture content (HMC) and three stress levels.

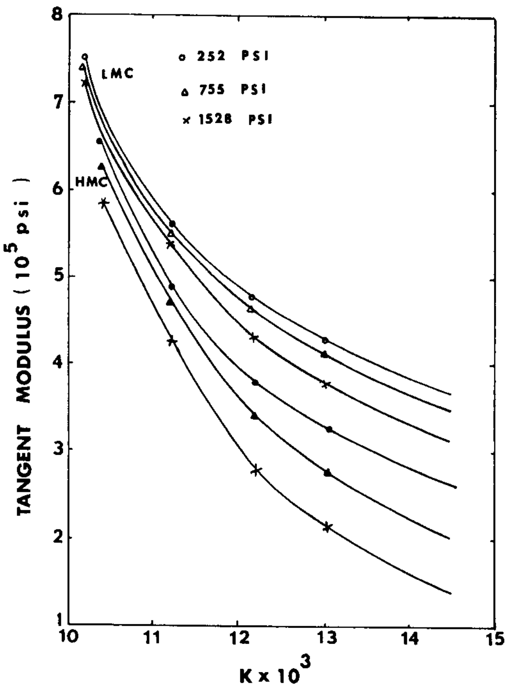

FIG. 4. Master modulus curves using Larson-Miller parameter $K = T\ (24 + \log t)$ for particleboard at both low moisture content (LMC) and high moisture content (HMC) and three stress levels.

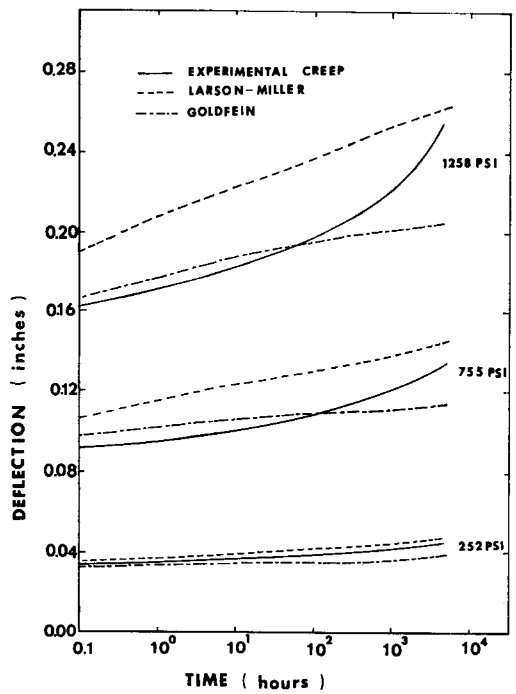

FIG. 5. The total deflection of particleboard at low moisture content (LMC) obtained under 70 F, 50% RH and at three stress levels. Experimental results and predictions derived from Figs. 3 and 4 using both Larson-Miller and Goldfein parameters are shown.

and high stress level, especially for boards of high moisture content.

Master tangent modulus curves, shown in Figs. 3 and 4, were constructed by using the relation for the parameter K given by eq. (1) and eq. (2). Two constants, C and t are required to determine the Larson-Miller parameter; and three constants, C, t and T_o are required for the Goldfein parameter. Goldfein explained that T_o is the temperature at which the strength of material is approximately zero. The method used in this study for determining T_o was linear extrapolation from the data shown in Fig. 1. Equation (3) and eq. (4) indicate that T_o is 543 F (1003 R) for board of low moisture content and 380 F (840 R) for board of high moisture content. T is the test temperature expressed in degrees Rankine. The C value that has been most used in metals, plastic and hardboard is 20 (Gloor 1958 and Haygreen and Sauer 1969). The magnitude of C is probably different for each material and can be considered as a material constant. In this study, an empirical value of 24 for C was found to provide a reasonable fit to the long-term data with both the Larson-Miller and the Goldfein parameter. Because t is the time under constant load, a steady load-time equivalent ($SLTE$) must be determined or assumed for these tests which were conducted under increasing load. In this study a value of 10^{-3} hr was assumed. The master tangent modulus curves shown in Figs. 3 and 4 were plotted using the K value for each temperature T computed as follows:

Larson-Miller parameter

$$K = T\ (24 + \log 10^{-3})$$

Goldfein parameter

$$K = \frac{T\,T_o}{T_o - T}\ (24 + \log 10^{-3})$$

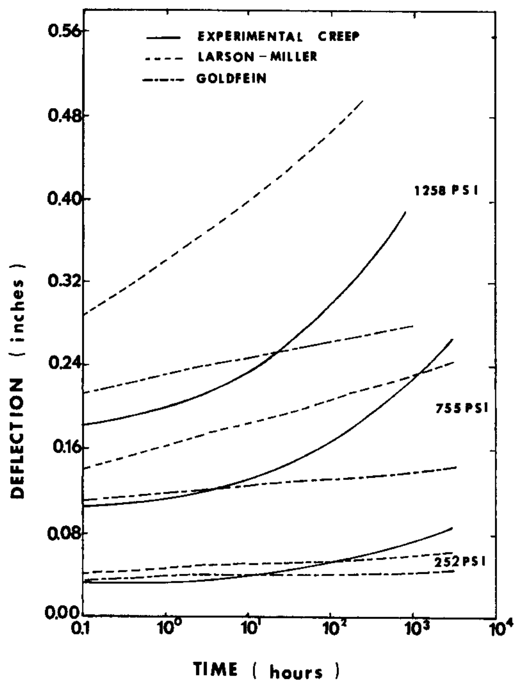

FIG. 6. The total deflection of particleboard at high moisture content (HMC) obtained under 70 F, 80% RH and three stress levels. Experimental results and predictions derived from Figs. 3 and 4 using both Larson-Miller and Goldfein parameters are shown.

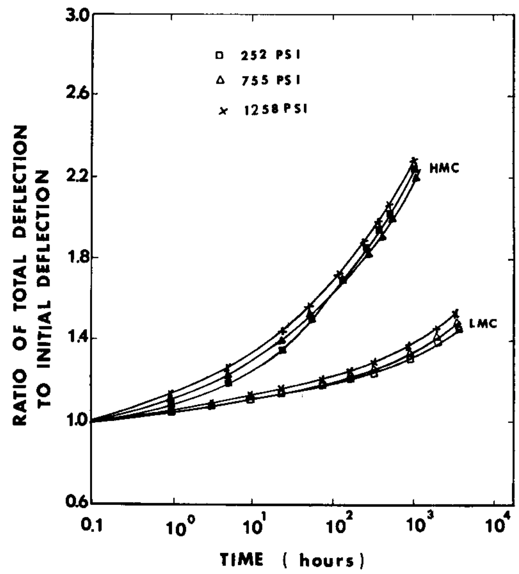

FIG. 7. Relative creep of particleboard at both low moisture content (LMC) and high moisture content (HMC) obtained under 70 F, three stress levels and 50% and 80% RH.

where T_o is 1003 R at low moisture content, and 840 R at high moisture content. For example, when test temperature is 72 F (532 R), the Larson-Miller parameter (K) is 11.2×10^3 for both low and high moisture content, and the Goldfein parameters (K) are 23.8×10^3 and 29.8×10^3 for low moisture and high moisture content respectively. The master tangent modulus curves were made by plotting the corresponding tangent modulus vs. K values as shown in Figs. 3 and 4.

Figures 5 and 6 show the total deflection of a beam of particleboard under midpoint loading at the two moisture content levels and three stress levels. The values are averages from 12 tests. Increasing the moisture content of boards from 7 to 10% had a very pronounced effect on the total creep deflection. After 1000 hr, the total deflection of boards at the high moisture content was about 1.9 times greater than that of boards at the low moisture content. Eight of the twelve specimens stressed to 1258 psi at 10% moisture content had failed before 2000 hr. Only two specimens of low moisture content stressed to the same level failed during the tests.

In Fig. 7, relative creep is shown as the ratio of total deformation to the deformation at 0.1 hr. It confirms the fact that relative creep does not vary greatly for different stress levels at a constant moisture content (Bryan 1960 and Bryan et al. 1965). There is a considerable difference, however, between moisture content levels.

The predicted creep and the experimental results are shown in Figs. 5 and 6. The predicted values were calculated from the master tangent modulus curves shown in Figs. 3 and 4 by using both the Goldfein and Larson-Miller parameters.

The actual long-term creep tests were conducted at 70 F (530 R). In predicting creep with Goldfein parameter, K values were computed from a T value of 530 R and T_o values of 1003 R and 840 R for low and high moisture content respectively. The same T of 530 R was used in computation of the Larson-Miller parameter. A C value of 24 was found empirically to provide a reasonable fit to the experimental values. For example, if the testing time t is 10^2 hr, and the test temperature is 530 R, the K values are 13.8×10^3 for both low and high moisture content using the Larson-Miller equation and 29.2×10^3 and 37.3×10^3 for low moisture and high moisture content respectively using the Goldfein equation. By the interpolation from Fig. 3, tangent modulus values of 4.6, 4.5 and 4.2×10^5 psi can be obtained for the low moisture content boards at stress levels of 252, 755 and 1258 psi. The predicted deflections of 0.034, 0.11 and 0.34 inch are shown in Fig. 5.

Both Larson-Miller and Goldfein parameters provide reasonable estimates at the low stress levels. At high stress levels the Larson-Miller parameter provides more a conservative estimate of the behavior in the 1000–3000 hr range. Neither method predicts accurately the increasing creep at the higher stress levels and longer times.

CONCLUSION

The potential advantage of the use of a time-temperature relationship in a form such as Larson-Miller and Goldfein parameters is the fact that it is possible to predict long-term behavior at any temperature without performing a single test at that temperature or for that long time. Particleboard exhibits a hyperbolic deflection-log time relationship under all conditions studied while deflection predicted from tests at elevated temperatures is nearly linear with log of time. From a practical viewpoint, although the accuracy of both prediction methods diverges at extended times, the prediction methods could give approximate estimates. A stress level ranging from 10 to 20% of the modulus of rupture may be about the highest stress which is of practical interest in structural applications of particleboard that are to be continuously loaded. At these stress levels, Larson-Miller parameter provides a more conservative estimate of deflection values for design purposes than the Goldfein parameter. This study concerned only particleboard subjected to a constant equilibrium moisture content condition. Only one type of particleboard was studied. Much more extensive testing would be required to determine the general applicability of these methods to other types of boards and for conditions of changing moisture content.

REFERENCES

BRYAN, E. L. 1960. Bending strength of particleboard under long term load. Forest Prod. J., **10**(4):200–204.

BRYAN, E. L., AND A. P. SCHNIEWIND. 1965. Strength and rheological properties of particleboard as affected by moisture content and sorption. Forest Prod. J., **15**(4):143.

CAREY, R. H., AND E. T. OSKIN. 1956. The prediction of long time stress rupture data from short time tests. Soc. Plastics Eng. J., **12**(3):21–25.

C.S.I.R.O. Aust. Div. Forest Prod. Ann. Report 1966/1967 and 1967/1968.

GLOOR, W. E. 1958. Application of Larson-Miller correlation to service test data on high density polyethylene. Mod. Plastics, **36**(2): 144.

GOLDFEIN, W. E. 1954. Time temperature relationship for rupture stresses in reinforced plastics. Proc. ASTM, **54**:1344–1365.

GOLDFEIN, S. 1960. General formula for creep and rupture in plastics. Mod. Plastics, **37**: 127–132.

HAYGREEN, J., AND D. SAUER. 1969. Prediction of flexural creep and stress rupture in hardboard by use of a time-temperature relationship. Wood Sci., **1**(4):241–249.

HOLLOMAN, J. H., AND L. C. JAFFE. 1945. Time-temperature relations in tempering steel. Trans. Am. Inst. Mining Met. Eng. Iron & Steel Div., **162**:223–249.

LARSON, F. R., AND J. MILLER. 1952. A time-temperature relationship for rupture and creep stresses. ASME. Trans., **74**(5):765–771.