EFFECT OF TEMPERATURE AND STRESS ON THE TIME-TO-FAILURE OF EPDM T-PEEL JOINTS

JONATHAN W. MARTIN, EDWARD EMBREE and DALE P. BENTZ

Center for Building Technology, National Bureau of Standards
Gaithersburg, Md.

Creep-rupture experiments were conducted on adhesively bonded EPDM T-peel seams to determine the sensitivity of their time-to-failure distributions to temperature and mechanical stress. Experimental results indicate that time-to-failure distributions are very sensitive to mechanical stress, but not temperature. That is, at a given temperature, as mechanical stress increases, in the time-to-failure distributions decrease. However, at a given stress, changes in temperature do not cause a significant change in the time-to-failure distributions, except at the lowest experimental stress level where an increase in temperature may result in an increase in the times-to-failure. This increase, at the lowest experimental stress, is due to the formation of fibers between separating seam plies. This change in failure mode at the lowest experimental stess level may limit the use of temperature and stress as acceleration factors.

Key words: Accelerated aging, creep-rupture, EPDM, roofing, single-ply, temperature, time-to-failure, T-peel, Weibull distribution.

In 1985, more than half of the single-ply membrane material sold in the United States was EPDM (ethylene-propylene-diene terpolymer).[1] EPDM's market dominance can, in part, be attributed to its good field performance, which in turn can be attributed to the chemical inertness of EPDM. Chemical inertness, however, makes EPDM a very difficult surface to wet with an adhesive and thus, to form a durable field seam. The field-prepared seam, therefore, appears to be one of the weak links in an EPDM roofing system.[2] This assessment is consistent with NRCA's Project Pinpoint statistics,[3] where seam failure is reported as the single greatest problem for single-ply roofing systems.

Failure of seams in the field can result from a multitude of factors including: 1) poor surface preparation of the membrane material or improper application techniques; 2) chemical and physical aging of the membrane, adhesive or both; and 3) mechanical loads. Mechanical loads result from changes in temperature and are caused by the large thermal expansion coefficient differences between the membrane and other roofing deck materials.[4] Thus, relative to the steel deck, a decrease in temperature will result in the seam being subjected to a tensile lap-shear stress. An increase in temperature will cause the membrane to buckle at the seam, subjecting it to a peel-type stress. Seam failure occurs whenever the applied stress exceeds seam strength. The time, which elapses from seam formation to seam failure, is called the service life of a seam.

At present, knowledge of the causes of in-service seam failure is limited and questions remain in several key areas: 1) the role of tensile-lap shear and peel-type stresses in causing seam failures; 2) the effect of the diurnal cycle; 3) the relative importance of surface preparation and adhesive and membrane film aging; and 4) the effects of moisture, temperature, and mechanical stress on the time-to-failure of a seam. To address these questions, the National Bureau of Standards (NBS) has initiated an accelerated aging program to identify those material and processing variables which determine the service life of a single-ply roofing seam subjected to its intended operating environment.

Service life data can be obtained from either outdoor or accelerated aging tests, but due to time and monetary constraints, only accelerated aging tests provide a practical means for generating valid service life data. In designing a valid accelerated aging test, an acceleration factor must be chosen such that degradation is accelerated without introducing failure modes atypical to those experienced in-service and without making the test so complicated that service life predictions become mathematically intractable. Due to the limited knowledge of the causes of seam failure, the objectives of the present research were narrow. Specifically, they were to determine the sensitivity of the time-to-failure distributions to different temperature and mechanical stress levels for a single population of adhesively bonded EPDM T-peel seams exposed to these stresses and to determine if either temperature or mechanical stress may be considered as an acceleration factor.

Creep-rupture tests

Specimen Preparation: 236 T-peel specimens (Fig. 1) were cut from a 1.8m x 4.6m (6 feet x 15 feet) commercial EPDM sheet. The width of each T-peel specimen was 25.4mm and the length was 127.0mm (1 inch x 5 inches), of which 76.2mm (3 inches) was adhesively bonded. Prior to applying the adhesive, the EPDM membranes were cleaned with soapy water, rinsed with tap water, and allowed to dry at laboratory conditions for 24 hours. They were then cleaned with a propriety solvent, available from the membrane manufacturer, and dried for one hour at laboratory conditions. A commercially available polychloroprene (neoprene) adhesive, also supplied by the membrane manufacturer, was then brushed on both plies of the T-peel specimens, and allowed to dry for 15–20 minutes. The two plies were then pressed together in a hydraulic press for 15 seconds at 3.5 MPa (500 psi), removed from the press, and allowed to cure in the laboratory for 7 days at 22°C (72°F) and 45 percent r.h. After 7 days, 20 control specimens were randomly selected from the 236 specimens and tested in peel at a crosshead speed of 50mm/min (2 in/min). The average peel strength for the controls was 795 N/m (4.5 lb/in) with a standard deviation of 108 N/m (0.61 lb/in).

Experimental design: The remaining 216 specimens were randomly assigned to one of 16 stress/temperature exposure levels as indicated in Table 1. The four stress levels, applied as a dead load, were 80, 155, 235, and 315 N/m (0.45, 0.90, 1.36, and 1.81 lb/in) and the four temperature levels were 30, 45, 60, and 75°C (85, 113, 140, and 167°F). After assignment, all specimens were stored in a freezer at −40°C (−40°F) for at least one week to minimize chemical changes to the adhesive, membrane, or both. Some specimens remained in the freezer for six months waiting for a creep-rupture apparatus to become available.

Creep-rupture tests were conducted in one of three humidity cabinets, each of which was maintained at 45 percent relative humidity (plus or minus 1 percent) and to within 1°C (1.8°F) of their assigned temperature. Each apparatus was designed such that all of the specimens in a cabinet were loaded simultaneously. Thus, the starting time for each specimen began when it first sustained its assigned load and ended when the plies of the seam physically separated, stopping the electronic clock attached to each specimen. Prior to loading, all specimens were conditioned at their assigned temperature for at least one hour.

Effect of storage temperature on T-peel strength

An independent experiment was conducted to determine the effect of storage temperature on peel strength. One hundred T-peel specimens were prepared and randomly assigned to one of two groups of 50; one group was stored in a freezer at −40°C (−40°F) and the other stored in the laboratory at 22°C (72°F) and 45 percent r.h. At the end of each week, for 10 weeks, five specimens were removed from both the freezer and the laboratory and tested in peel at a machine speed of 50mm/min (2 in/in). Specimens, stored in the freezer, were allowed to warmup to laboratory conditions for at least one hour prior to testing.

RESULTS

Effect of storage temperature on T-peel strength

In Fig. 2, the average of five T-peel strengths, along with a one standard deviation bound, is plotted as a function of storage time for specimens stored at −40°C (−40°F) and room temperature. For specimens stored at −40°C (−40°F), a significant drop from 755 to 560 N/m (4.3 to 3.1 lb/in) occurred in the T-peel strength during the first week of exposure, but after this initial drop, the peel strength remained constant. This initial drop is believed to result from the freezing of water in the T-peel joint. The water may be present in the adhesive[5] or deposited on the surface of the membrane prior to applying the adhesive. For specimens stored at room temperature, T-peel strength gradually decreased over the 10-week storage time. This decrease was found to be statistically significant and after seven weeks of storage, the expected T-peel strength, determined from the regression line, fell below that of specimens stored in the freezer. The cause of this decrease in T-peel strength with time for specimens stored at room temperature is under investigation.

Creep rupture time-to-failure distributions

When all specimens are subjected to the same exposure conditions and tested together, observed times-to-failure are ordered; that is, the weakest specimen fails first, followed by the failure of stronger specimens. From these ordered times-to-failure, an empirical cumulative distribution can be constructed and fitted with an appropriate "theoretical" distribution. The "theoretical" distribution that fit the data was the Weibull distribution which has the form:

$$F(t) = 1 - \exp(-(t/\beta)^{\alpha}) \text{ for } t > 0$$

where

α and $\beta > 0$

$F(t)$ is the Weibull cumulative distribution function and 100 X $F(t)$ equals the cumulative percentage of failure,

α is the Weibull shape parameter,

β is the Weibull scale parameter, and

t is a time.

The Weibull distribution has emerged as the most popular parametric family of failure distributions for fitting early time-to-failure data[6] and has been successfully used in modeling the times-to-failure of a wide-range of materials, components, and systems.[6,7]

Empirical distributions at each mechanical stress and at all four test temperatures are plotted in Figs. 3–6 with their corresponding Weibull distributions curves superimposed. In Figs. 3–6, specimen times-to-failure are indicated by dots. The tails, extending to the right from each time-to-failure, are used to determine the goodness-of-fit of a theoretical distribution to its empirical distribution and are drawn from one time-to-failure to the next, higher ordered time-to-failure. The tail, therefore, depicts the time which has elapsed between successive failures. A theoretical distribution, the solid continuous lines Figs. 3–6, is said to fit an empirical distribution well if it intersects most of these tails or times-to-failure. Estimates of the Weibull distribution parameters along with other statistics are presented in Table 2. In Figs. 4–6, the 80 N/m (0.45 lb/in) time-to-failure data are not plotted, since at most one time-to-failure was observed at these temperatures.

Time-to-failure distributions at different stresses, constant temperature

For specimens exposed at the same temperature, as mechanical stress increases, the distributions of the times-to-failure stochastically decrease (Figs. 3–6); i.e., as the level of mechanical stress increases, the times-to-failure, in general decrease. This can also be seen by plotting the Weibull shape parameter, α, and the logarithm of the Weibull scale parameter, $\log_{10} \beta$, against applied stress (Figs. 7 and 8). The Weibull shape parameter, α, was not found to be statistically different from one stress to another over the experimental stress range. The Weibull scale parameter, B, does change significantly, however, with applied stress. For the three highest stress levels, the logarithm of the Weibull scale parameter is a linear function of applied stress (Fig. 8). At the low stress, 80 N/m, however, the slope of the logarithm of the Weibull scale parameter, B, versus applied stress curve appears to change (the dashed line Fig. 8) indicating a change in failure mode. The reason for this slope change will be discussed subsequently.

Time-to-failure distributions at different temperatures, constant stress

For specimens subjected to stress levels greater than 80 N/m, a change in temperature does not result in a significant change in the times-to-failure distribution (Fig. 9). For specimens subjected to 80 N/m (0.45 lb/in), however, an increase in temperature appears to increase the times-to-failure. For example, at 30°C (86°F), all specimens failed within 1300 h (see Table 2); whereas, at the three higher temperatures, one or no failures were observed over this same time period, indicating an increase in creep-rupture life with temperature at the lowest stress level, 80 N/m.

Failure mechanism at the lowest stress level

At the lowest stress level, 80 N/m (0.45 lb/in), fibers (also called legs) formed between the separating T-peel plies (Fig. 1). The formation of fibers is important because they strengthen the seam, by supporting additional tensile stress,[8] and increase the creep-rupture life of the specimen. At 80 N/m, fibers formed at all four temperatures except for the two specimens which failed, one at 60°C (140°F) and the other at 75°C (167°F) (Table 2). At stress levels greater than 80 N/m (0.45 lb/in), fibers did not form.

To support the conclusion that fibers strengthen T-peel joints, three specimens, stressed at 80 N/m (0.45 lb/in) and 45°C (113°F), for 1336 h, were removed from the test chamber and tested in peel at a machine speed of 50mm/min (2 in/min). The average T-peel strength for these three specimens was 1750 N/m (10 lb/in) which is about two and a half times greater than the average peel strength of the controls, which was 795 N/m (4.5 lb/in). From the plot of peel strength versus peel distance (Fig. 10), all of the additional strength occurs at the beginning of the peel test where the fibers formed. Upon application of the load, these fibers sustain stress and elongate to the point where they begin to fail. During this elongation, new fibers are not formed, since the peel rate is greater than the relaxation time of the macromolecules. Hence, once all of the original fibers break, the peel strength reverts to that of the control specimens.

To support the conclusion that fibers increase service life of T-peel specimens, five specimens, originally stressed at 80 N/m (0.45 lb/in) and 45°C (113°F) for 1336 h, were stressed at 155 N/m (0.90 lb/in) and 45°C (113°F) for an additional 1000 h. None failed, whereas all of the specimens originally subjected to this treatment failed within 100 h (Table 2).

CONCLUSIONS

A creep rupture experiment was conducted to determine the sensitivity of the time-to-failure of EPDM T-peel specimens to different levels of temperature and mechanical stress. Concurrent with the creep rupture experiment, an experiment was conducted to determine the effect of storage temperature on T-peel strength. From these experiments, the following conclusions can be made:

- At each of the experimental temperatures, as mechanical stress increased, the distributions of times-to-failure decreased.
- At the lowest stress level, fibers formed between the separating T-peel plies at all four experimental temperatures. Fiber formation greatly increased both the strength and creep-rupture life of the T-peel specimens.
- At a given stress level, the distributions of times-to-failure were independent of a change in temperature, except at the lowest stress level where the time-to-failure distributions appear to increase with an increase in temperature.
- For the experimental adhesive, T-peel strength decreased with storage time for specimens stored in the laboratory at room temperature. For specimens stored at −40°C, a significant drop in T-peel strength was observed during the first week of storage, but after this initial drop, no change in T-peel strength was observed. After seven weeks of storage, the strength of the T-peel specimens stored in the laboratory appeared to fall below that of the specimens stored in a freezer.

REFERENCES

[1] Toland, R.M., "Single-ply tops the market," *Contractors Guide,* March (1986).

[2] Westley, S.A.; Polaski, E.L., Seam adhesion of EPDM roofing membranes, Elastomers 116:13 (1984).

[3] Cullen, W.C., "Survey compares practices to problems," National Roofing Contractors Association *Roofing Spec.* 12(10):37 (1984).

[4] Rossiter, W.J.; Batts, M.E., Finite-element analysis of temperature-induced stresses in single-ply roofing membranes, Dur. Building Mat. 2:195 (1985).

[5] Steinfink, M., Neoprene adhesives: solvent and latex, in Handbook of Adhesives, 2nd edition, I. Skeist [ed], Van Nostrand, New York (1977).

[6] Mann, N.R.; Schafer, R.E., Singpurwalla, N.D., "Methods for Statistical Analysis of Reliability and Life Data," Wiley, New York, (1974).

[7] Martin, J.W., Time transformation functions commonly used in Life Testing Analysis, Dur. Building Mat. 1:175–194 (1982).

[8] Kaeble, D.H., Peel adhesion: micro-fracture mechanics of interfacial unbonding of polymers, Trans. Soc. Rheo. 9(2): 135 (1965).

Temperature °C	Stress 80 N/m (0.45 lb/in)	Stress 155 N/m (0.90 lb/in)	Stress 235 N/m (1.36 lb/in)	Stress 315 N/m (1.81 lb/in)
30	30	20	12	10
45	14	12	10	8
60	20	12	12	10
75	12	12	12	10

Table 1 *Number of specimens assigned to each temperature and stress level*

Stress (N/m)	Temp °C	No. on test	No. failed	1-st ttf[@] h	Last ttf h	Term. time h	Weibull scale β	Weibull shape α
80	30	30	29	6.77	1263.	1263.	305.91	0.99
155	30	20	20	1.24	31.	31.	9.05	1.13
235	30	12	12	0.31	4.55	4.55	1.96	1.48
315	30	10	10	0.20	2.11	2.11	0.76	1.51
80	45	14	0	*	*	1336.	?	?
155	45	12	12	12.47	82.9	82.9	42.00	2.18
235	45	10	10	0.76	8.18	8.18	3.36	1.67
315	45	8	8	0.37	0.79	0.79	0.54	3.69
80	60	20	1	48.00	*	3096.	?	?
155	60	12	12	1.57	71.94	71.94	25.29	1.05
235	60	12	12	0.10	2.91	2.91	1.17	1.29
315	60	10	10	0.09	0.50	0.50	0.27	2.19
80	75	12	1	10.50	*	4344.	?	?
155	75	12	12	3.22	19.18	19.18	11.37	1.88
235	75	12	12	0.09	3.81	3.81	1.82	1.18
315	75	10	10	0.03	0.37	0.37	0.16	1.33

[@] ttf—time-to-failure, which is measured from the time a T-peel specimen first sustains its assigned load to the time the membranes of the T-peel specimen physically separate.

* failure not observed

? number of failures too small to estimate Weibull parameters

Table 2 *Weibull distribution parameters for each treatment level*

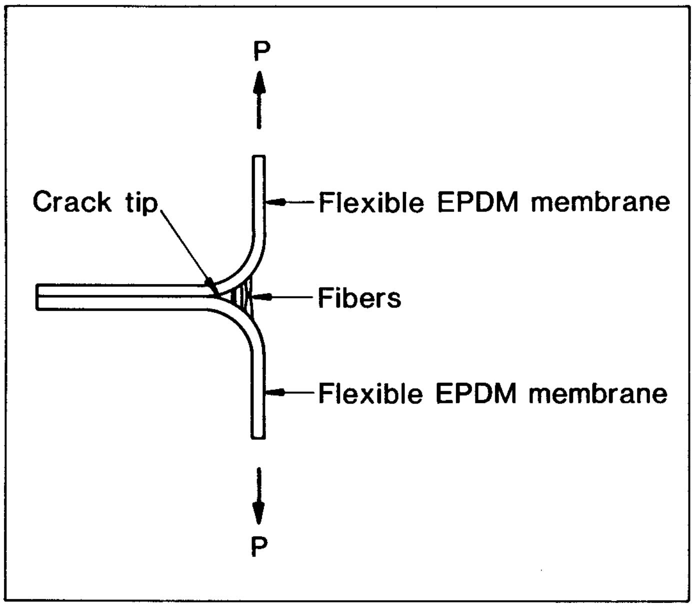

Figure 1 *Schematic representation of T-peel specimen and fiber formation between separating plies (adapted from Kaeble [8])*

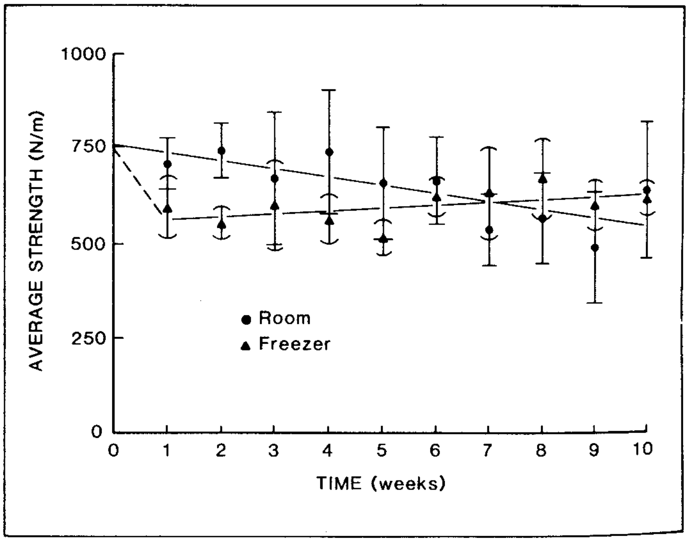

Figure 2 *T-peel strength versus storage time for specimens stored and tested at room temperature, 22°C (72°F) and at −40°C (−40°F)*

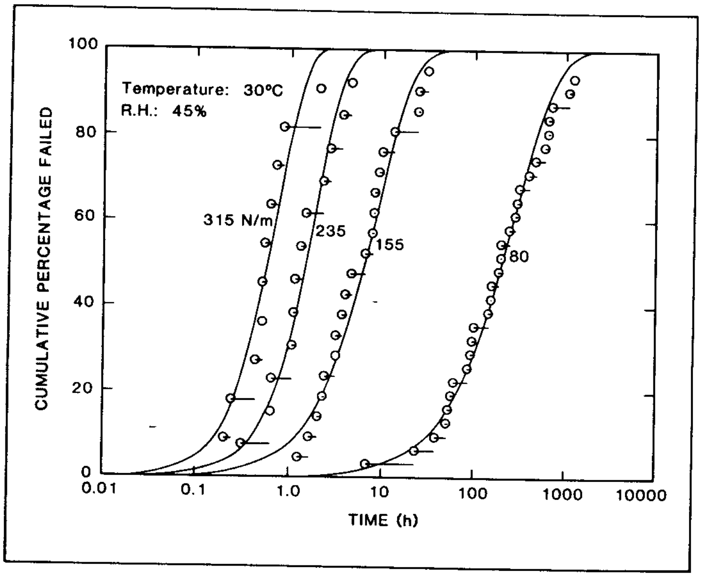

Figure 3 *Empirical and theoretical time-to-failure distributions for EPDM T-peel creep-rupture specimens exposed at 30° C (86°) and subjected to a mechanical stress of 80, 155, 235, and 315 N/m*

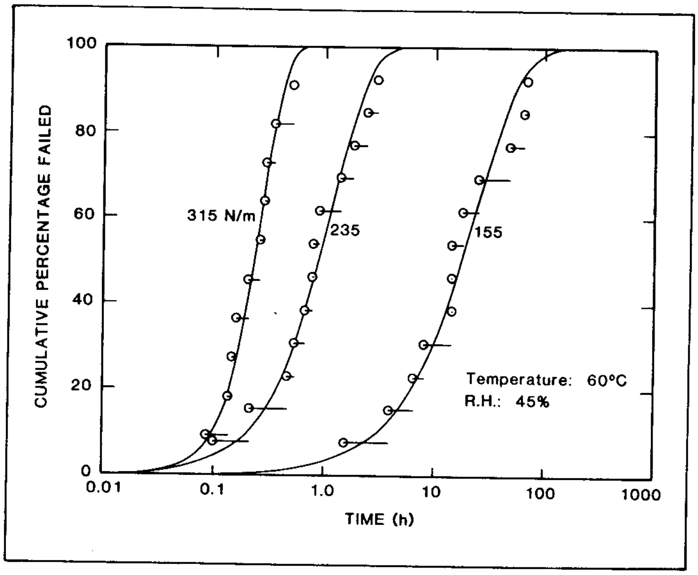

Figure 5 *Empirical and theoretical time-to-failure distributions for EPDM T-peel creep-rupture specimens exposed at 60° C (140° F) and subjected to a mechanical stress of 80, 155, 235, and 315 N/m. Times-to-failure at 80 N/m are not shown, since only one failure occurred prior to termination of test.*

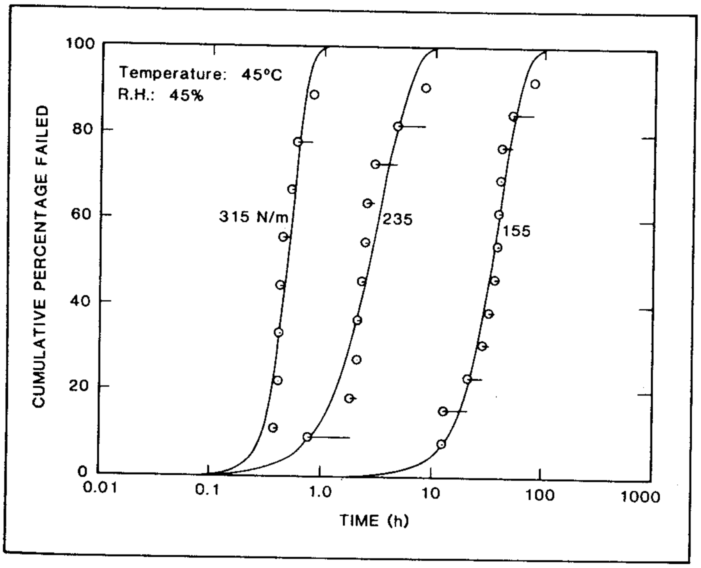

Figure 4 *Empirical and theoretical time-to-failure distributions for EPDM T-peel creep-rupture specimens exposed at 45° C (113° F) and subjected to a mechanical stress of 80, 155, 235, and 315 N/m. Times-to-failure at 80 N/m are not shown, since no failures occurred prior to termination of test.*

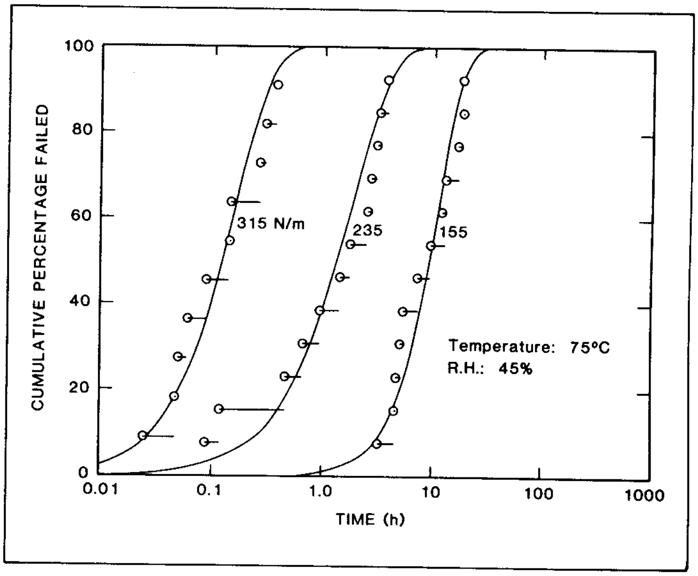

Figure 6 *Empirical and theoretical time-to-failure distributions for EPDM T-peel creep-rupture specimens exposed at 75° C (167° F) and subjected to a mechanical stress of 80, 155, 235, and 315 N/m. Times-to-failure at 80 N/m are not shown, since only one failure occurred prior to termination of test.*

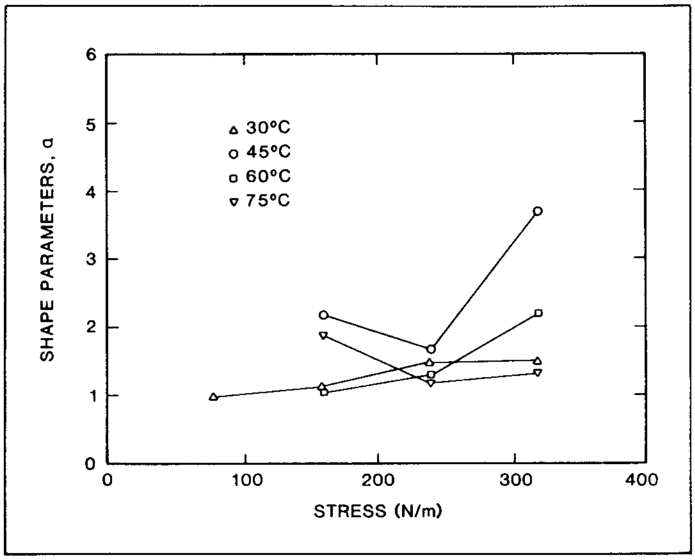

Figure 7 *The Weibull shape parameter versus applied stress at different temperatures*

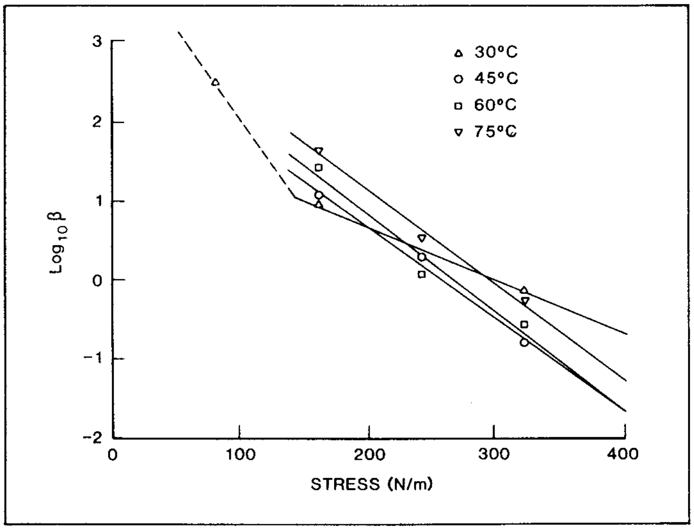

Figure 8 *The logarithm of the Weibull scale parameter versus applied stress at different temperatures*

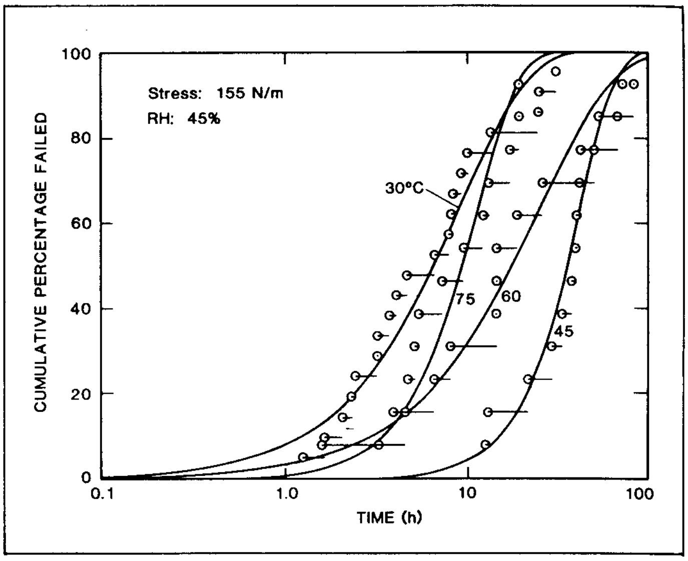

Figure 9 *Empirical and theoretical time-to-failure distributions for EPDM T-peel creep-rupture specimens subjected to a constant stress, 155 N/m (0.90 lb/in), and exposed at 30, 45, 60, or 75°C*

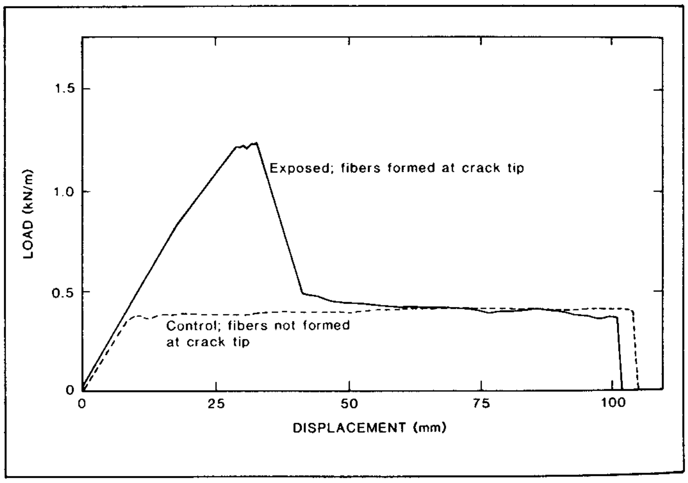

Figure 10 *T-peel strengths for a control and for a specimen which has been initially subjected to a creep-rupture stress of 80 N/m for 1336 h and then tested at 50mm/min in a standard peel test mode*