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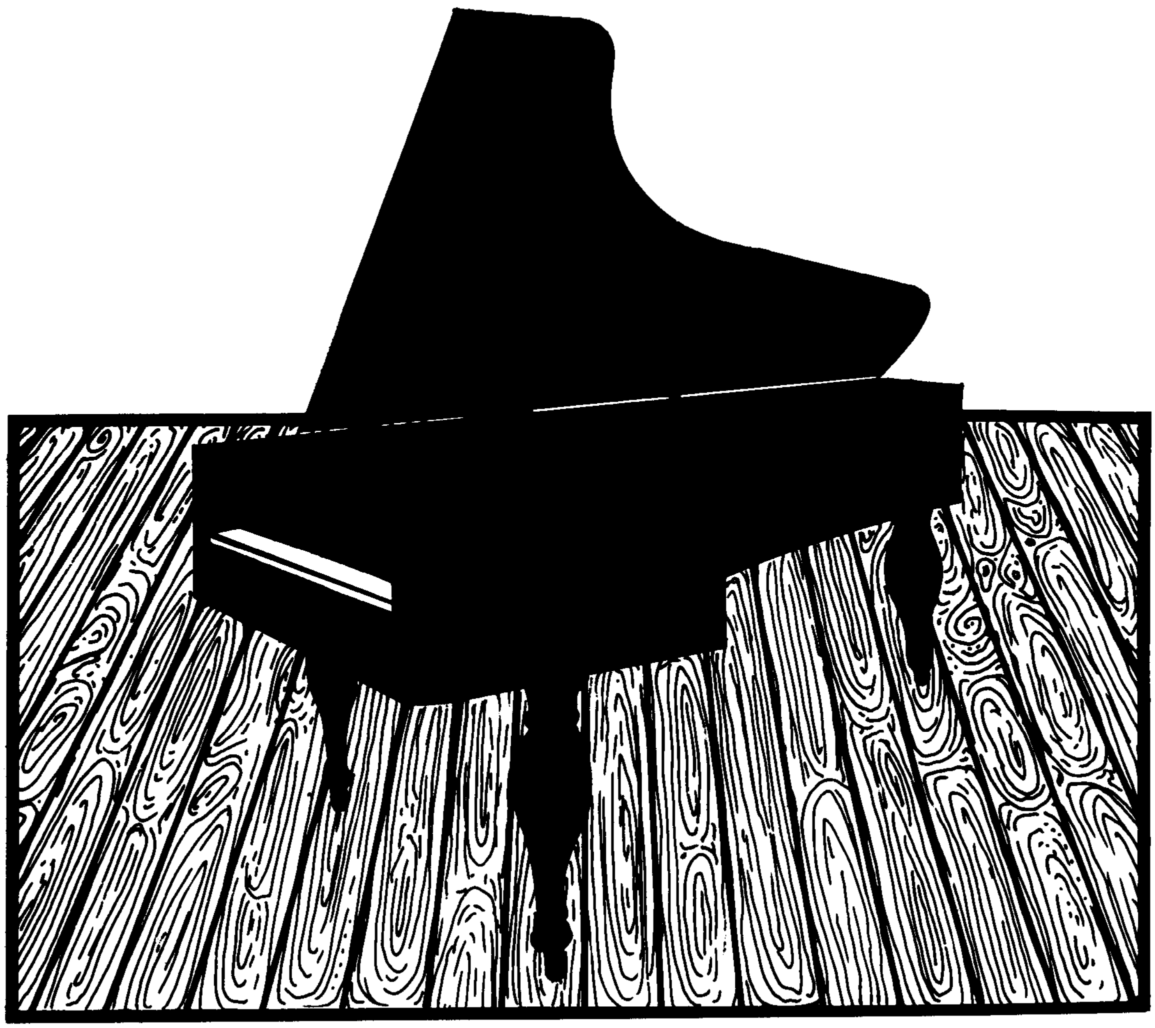
Behavior of Construction Adhesives Under Long-Term Load



Abstract

Six construction adhesives and a conventional polyvinyl acetate adhesive were placed under dead load at five stress levels and three temperatures for 2 months. The shear slip was measured after 10, 100, 1,000, 10,000, and 100,000 minutes (70 days) under load. The results show four general types of behavior. Three construction adhesives with crosslinking capability had fair resistance to creep and showed evidence that a creep limit might be reached under moderate dead load and environmental conditions. Two adhesives had very poor creep resistance and failed under moderate dead load and environmental conditions. The sixth adhesive was extremely flexible but with excellent recovery capability. A polyvinyl acetate adhesive was not observed to creep under the low humidity conditions of this study. Adhesives showing evidence of a creep limit may be useful for long-term design loads, but further study of their behavior, especially under varying moisture conditions, is required.

Conversion of Units

1 inch = 25.4 mm

1 lbf/in.^{2} = 6895 Pa

80° F = 27° C

120° F = 49° C

160° F = 71°C

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Behavior of Construction Adhesives Under Long-Term Load

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Introduction

The objective of this study was to investigate the effects of temperature and time on the rigidity of construction adhesives.

The use of construction adhesives[2] in the building industry has grown dramatically in recent years. The growth is based on certain unique advantages[3] that construction adhesives hold over nails or staples and conventional rigid adhesives. However greater growth and materials savings would be possible if designers fully understood the behavior of construction adhesives under long-term load and used these properties to design more efficient structures.

[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] The term “construction adhesive” is suggested by the American Plywood Association in its specification AFG-01, “Adhesives for Field Gluing Plywood to Wood Framing.” “Construction adhesives” are generally one-part elastomer-resin combinations, also including various metal oxides, fillers, solvents, or water, and other materials in a mastic consistency.

[3] Among the advantages most frequently cited over nails are: reduction in callback to repair nail pops or squeaky floors, labor and/or materials savings, general improvement in building quality. Advantages over rigid adhesives are: gap-filling capacity, low pressure requirement, and broad cure temperature range.

Adhesives, like nails, transfer stress from one structural member to the next. The efficiency of the fastening system depends on the rigidity of the joint formed by the system. Rigid adhesives such as phenol resorcinol formaldehyde are of course the most efficient. They are stronger and more rigid than the wood bonded and any change in their properties with time or temperature can not be detected. These facts have allowed designers to ignore the adhesive in designing structures fastened with phenol resorcinol adhesive. The mechanical properties of joints fastened with nails or staples (according to established standards) are also assumed by designers to be constant and are therefore ignored in the long term. Construction adhesives are less strong and less rigid than wood and therefore less efficient fasteners than the rigid adhesives but they are more efficient than nails and staples. Their major disadvantage is the lack of knowledge of how their strength and rigidity change with time.

The rigidity of a material is usually associated with shear. The shear modulus is defined as the ratio of shear stress to shear strain within the elastic region. With quite rigid materials, the shear modulus is considered to be a constant value regardless of the length of time the stress is applied; but few, if any, materials are truly rigid in this sense. Even the “rigid” adhesives will continue to deform under load but at such a small rate that it can be ignored. On the other hand, less rigid materials such as the construction adhesives are viscoelastic and will continuously creep and markedly deform under load. In this case, the rigidity is better defined as a creep modulus, which is a load- and time-dependent property. Creep modulus is the ratio of the initially applied stress to the total strain resulting during the time the stress is applied. It is important to know how the creep modulus changes with time under a variety of loads and environments.

In this report, the term "creep modulus" will be used to describe the rigidity of an adhesive under long-term continuous loads. The term "shear modulus" will refer to a measurement under light loads applied for short time periods-approximately 3 minutes or less. The creep modulus of rigid adhesives does not vary with time. The creep modulus of nonrigid adhesives such as construction adhesives, however, may continuously decline with time. This must be considered an important factor in the design for long-term performance of a composite structure bonded with construction adhesive.

Research at Forest Products Laboratory *(6)*[4] has shown that composite systems employing adhesives, less rigid and not as strong as wood, can be rationally designed for live loads. Hoyle *(4)* applied this design method to "I" beams bonded with construction adhesives of several rigidities, and expanded the scope to encompass performance of the composite under loads for as long as 1 to 2 months. Hoyle found that adhesives with shear moduli as low as 100 pounds force per square inch (lbf/in.^{2}), when used in a properly-designed component, could develop more than 50 percent of the composite action attainable with a rigid adhesive whose shear modulus might be greater than 100,000 lbf/in.^{2}. Krueger *(5)* and Richards *et al. (7)* have demonstrated that flexible adhesives in bonded structural components may significantly reduce stress concentrations within the components and allow better use of materials than do rigid adhesives.

Further work toward designing structures with construction adhesives, and predicting how they will perform, depends upon the development of reliable information about how adhesives behave under loads. How much an adhesive creeps under dead loads and how much of the creep is recoverable upon removing the load are both important.

The measurement of creep phenomena must take into consideration the effects of such factors as the quality of the initial bond, bondline thickness, temperature, humidity, stress level, and the duration of load.

This study was designed to measure the load-deformation behavior of construction adhesives in controlled-thickness, well bonded joints as a function of time under load at different temperatures and stress levels, and constant humidity.

[4] Italicized numbers in parentheses refer to literature cited at end of this report.

Terminology

Load.–The force (lbf) applied to the specimen at any given time. In creep testing, the load is a constant or dead load applied for 3 minutes or longer.

***Shear stress.*–**The force per unit area (lbf/in.^{2}) tangential to the plane on which the forces act.

Shear strain (3).–*The* tangent of the angular change (in./in.), due to force between two lines originally perpendicular to each other through a point in the body.

Shear slip.-The parallel displacement (in.) due to force on two points located opposite each other at the bond interfaces. Adhesive layer thickness or thickness change under load is discounted.

Proportional limit (3).–*The* greatest stress (lbf/in.^{2}) a material is capable of sustaining without any deviation from proportionality of stress to strain.

Shear modulus (1).–*The* corresponding ratio of shear stress to shear strain (lbf/in.^{2}) for shear stresses below the proportional limit in shear of the adhesive, under short-term (live load) conditions.

Shear strength (1).–*The* maximum shear stress (lbf/in.^{2}) existing in the adhesive prior to failure, under short-term loading.

Creep ***(3).–****Time-dependent* increase in strain (in./in.) in a solid, resulting from force.

Note: The term "creep," as defined in ASTM E 6 *(3)* and as generally used in rheology, is the nonelastic portion of strain. In actual practice, however, it is difficult to separate the elastic and nonelastic portions of strain of most flexible adhesives. Therefore, such a definition is not practical in the measurement of creep behavior or in applying the measurements to engineering design. The definitions for creep strain and creep modulus below reflect current plastics engineering usage and will be used in this report.

Creep strain (2).–*The* total strain (in./in.) at any given time produced by the applied stress during a creep test.

Creep ***modulus (2).–****The* ratio of initial applied stress to creep strain (lbf/in.^{2}).

Creep recovery ***(3).–****Total* decrease in strain (in./in.) following the removal of force. (In plastics the total decrease in strain is used.)

Creep rupture strength (3).–*The* stress (lbf/in.^{2}) that will cause fracture in a creep test in a specified time and environment.

Materials and Methods

Adhesives

Seven commercial adhesives were examined in this study. Six (A,B,C,E,K,V) were construction adhesives. The seventh adhesive (EE), which was included for comparison, was a conventional high-resin-solids polyvinyl acetate resin emulsion, a thermoplastic not of mastic consistency.

Adhesive “A” was a 100 percent solids, extremely high-viscosity material which cures to a very flexible, rubbery adhesive layer, uniformly permeated by minute voids.

Adhesives B, C, and V, represented a second elastomer base with solids of 57, 53, and 54 percent, respectively. These three adhesives each form a tough, hard adhesive layer. Likewise, all three tend to “honeycomb” as solvent is lost from the glueline.

“Honeycombing” refers to the condition of the glueline after the solvent is lost–i.e., the glueline is full of large and small voids. Honeycombing is most severe in thick joints, with adhesives of low solids content, and especially in joints where the adherends are restrained from drawing together as solvent is lost and the adhesive shrinks. In thick bondlines with enforced gaps, the voids may coalesce until the entire center of the joint is a large void and the adhesive forms a bond only along the edges of the joint. The amount of honeycombing and the thickness of the walls between voids may also be affected by other factors in a localized area such as earlywood or latewood. The bond strength of these adhesives is extremely variable because of variable honeycombing, but, in general, adhesives B and C are stronger than V.

Adhesive E has the highest solids content (70 pct) among the solvent-dispersed construction adhesives. It, too, forms a hard, tough adhesive layer. Honeycombing occurs as adhesive E loses solvent, but the problem is less severe than in B, C, and V.

Adhesive K represents the fourth elastomer base. Its solids content is 58 percent; it cures to a very hard layer. Honeycombing does occur, but it is not as severe as in adhesives B, C, and V.

The constituents of adhesives are often changed in response to supply and price. Adhesive manufacturers, when they must change a constituent, will strive to maintain performance. Nevertheless, the adhesives used in this study may not be representative of those adhesives now on the market.

Specimen Design and Preparation

Test specimens were formed by bonding two 5/8- x 1- x 30-inch strips of hard maple *(Acer saccharum)* (fig. 1). Bondline thickness was controlled by 1/64-inch shims placed in the glueline. Maple was used for maximum stiffness to minimize peel stress in the joints under load. Saw kerfs were made through the adherends on alternate sides of the specimen to provide shear test areas of 1.0, 1.25, 1.67, 2.5, and 5.0 $in.^2$ (fig. 1). The stress in the successively larger areas was 80, 60, 40, and 20 percent of the stress in the 1-$in.^2$ joint. Shims were located in the 2.5-inch lengths of the specimen between the shear test areas.

The maple adherends were conditioned to approximate equilibrium moisture content at ambient laboratory conditions (80°F, 15-20 pct RH). Bonding and cure were carried out in the same environment. A 1/4- to 5/16-inch bead of adhesive was applied along the centerline, for the length of one of each pair of adherends. The adherends were mated and enough pressure applied along the specimen to press the top adherend to the shims. The amount of pressure applied varied from adhesive to adhesive, depending on its viscosity. All joints were cured a minimum of 30 days. Saw kerfs to form the test lap joints were cut after the 30-day cure period.

Test Apparatus and Arrangement

Specimens were supported on frames located in a temperature-controlled room. The specimens were suspended by a chain and hanger assembly from the frames with the largest joint at the top. A pan of weights was suspended from the lower end of each specimen. Eleven thermocouples were placed close to the specimens along both sides of the test chamber to monitor conditions within the room. An additional thermocouple was placed in the glueline of one specimen to measure the temperature variation at that position.

Test Environment

Separate groups of specimens were exposed to each of three temperatures, 80°F, 120°F, and 160°F). These temperatures were selected because they are representative of the maximum temperatures that can be expected in the floors, walls, and roofs respectively of buildings over much of the United States. The temperature-controlled room was a dry kiln equipped with three high-velocity fans to provide rapid circulation and cross circulation. Humidity was not directly controlled, but, by conducting the 80°F tests in the winter, the 120°F tests in spring, and the 160°F tests in summer, the relative humidity in the temperature-controlled room never exceeded 20 percent.

Stress Levels

Dead loads were chosen on the basis of limited knowledge of each adhesive’s capability. A single dead load on a specimen produced a different stress level in each specimen’s five test joints. A level of dead load was selected for each adhesive which was expected to yield measurable shear slip in even the largest test joint (lowest shear stress). The applied stress levels are shown in table 1. Four replications (specimens) of each adhesive were tested at each temperature.

Measurement of Shear Slip

Prior to loading, a reference line was scribed on each shear test joint perpendicular to the glueline and across both adherends. Displacement of the line when the specimen was under load (the joint shear slip) was measured with a Gaertner linear traveling microscope, having 0.001-inch graduations and a 0.0001-inch vernier. With care to always approach the scribe lines from the same direction, the ability to reproduce a reading was about ± 0.0003 inch.

Measurements of shear slip were made after 10, 100, 1,000, 10,000, and 100,000 minutes under dead load. The latter two measurements are approximately 7 and 70 days.

Calculations

Shear slip values were used either directly to show shear deformation with time under specific loads or for calculating creep strain and creep modulus. Shear modulus is calculated by dividing shear stress by the corresponding shear strain. Ideally, this is an expression of Hooke's law which states that stress divided by strain is a constant when the deformation is confined to values below the proportional (elastic) limit of the material. Creep is calculated by dividing stress by creep strain. In this case, deformation can be beyond the proportional (elastic) limit where viscoelastic and plastic deformations take place. The creep modulus of a material is not a constant but varies with load, time, and temperature. Creep strain and creep modulus were calculated by:

$$\text{Creep strain} = \frac{\text{Shear slip at time t}}{\text{Adhesive layer thickness}}$$

$$\text{Creep modulus} = \frac{\text{Applied stress}}{\text{Creep strain at time t}}$$

Results and Discussion

Creep Behavior

A typical creep curve is curvilinear with three segments usually referred to as primary, secondary, and tertiary creep (fig. 2). When a dead load is applied rapidly, the purely elastic deformation can be represented by the shear slip at time zero (OA, fig. 2). In primary creep, the viscoelastic mechanism comes into play soon after loading, and the rate of strain declines to a relatively constant rate that characterizes secondary creep defined by the slope of the line BB'. The elastic deformations in primary creep are usually recoverable upon removal of load.

In secondary creep, the linear portion of the curve, elastic deformations may continue to occur along with viscous flow. The elastic deformation in secondary creep can be considered as potentially recoverable. When the rate of creep again appears to increase, it is usually considered that the system is entering tertiary creep, which is predominantly viscous flow with rupture of the material soon to follow.

Figures 3 through 5 exemplify the behavior of adhesives C, A, and K, repectively, in this study. Shear slip is plotted against the logarithm of time to 10^5 minutes, or approximately 70 days (each curve is the average of four specimens).

From the creep curves, it was often difficult to specify if the material was deforming in the primary or secondary stages because the first readings were taken 10 minutes after loading. Apparently, the primary or even the secondary stage of creep had occurred for some adhesives during that interval. In a few cases, the linear portion of the curve passed through the origin when extrapolated back to zero time. This suggests that the curve illustrated essentially primary creep behavior. But in most cases, such an extrapolation to zero time yielded a sizable shear-slip value, suggesting that the curve illustrated secondary creep, and that primary creep had occurred during the first 10 minutes when no deformation values were obtained. This confusion might have been avoided if two or three readings could have been made before the initial 10 minute reading. Future studies will be automated to obtain the complete creep curve. Tertiary creep is more readily recognized as a curvilinear response with increasing time of loading.

The shear slip for adhesive C (fig. 3) varied approximately linearly with the log of time at 80°F and the response at both stress levels appears to be primary creep. At 120°F, secondary creep predominated, while at 180°F, tertiary creep became evident. The resistance of adhesive C to deformation under dead loads is quite temperature sensitive. A similar behavior was noted for adhesives B and V.

Adhesive A (fig. 4) showed less temperature sensitivity than adhesive C in the initial stage at all stress levels. But as time under load increased, the more highly stressed specimens exhibited curvilinear responses for adhesive A at 120°F and 160°F, with shear slip progressing at ever-increasing rates. Secondary creep appeared to predominate at all stress levels at 80°F, but at 120°F, tertiary creep became evident at the three highest stress levels, and at 160°F, all stress levels produced tertiary creep.

With adhesive K (fig. 5), there is evidence of tertiary creep at all three temperatures, even at stresses as low as 5-10 lbf/in.^{2}. At short times under load, adhesive K appeared to be quite insensitive to temperature, and did not indicate any elastic or viscoelastic type of response; only plastic deformation was exhibited at these low loads. Adhesive K did not display any potential for use under long-term loading even under low stress.

Because nails have been used successfully in wood construction for many years, a reasonable guideline for evaluation of adhesive shear slip might be that which is associated with recoverable shear slip of nailed joints. Wilkinson has found a slip value of about 0.012 inch to be the amount that will occur in a nailed joint without exceeding the proportional limit of the wood supporting the nail *(9).*

In the case of adhesive C (fig. 3), the shear slip at 70 days is comparable to, or less than, that of a nailed joint only at room temperature and the lowest stress levels, 80 and 40 Ibf/in.^{2}. Adhesive A (fig. 4), on the other hand, provided a shear slip at 70 days of approximately 0.012 inch or less at all three temperatures and the three lower stress levels ranging from 8 to 4 Ibf/in.^{2}.

The long-term load-deformation properties of adhesives can be compared on the basis of the total shear slip that takes place during a specified loading period. Slip data recorded after 70 days under dead load are shown in table 2. The large numbers of failures of adhesives E and K clearly identify these adhesives as having poor load-carrying capacity. Even at low stress levels, many failures occurred in less than 70 days under load. Neither adhesive could resist loading at temperatures above 80°F. Adhesives B, C, and V showed considerable deformation at high stress levels and high temperatures, with failures occurring in some cases, and bondline slip approaching 0.1 inch in others. The shear slip of adhesive A was less sensitive to temperature changes than any of the other adhesives.

The adhesives also differed with regard to the percentage of the total deformation (70 days) that took place upon initial loading (10 minutes). Adhesives E and K deformed very little, if at all, during the first 10 minutes under load at any of the stress levels evaluated (table 3). Adhesives A, B, C, and V, had initial deformations as high as 60 percent of the total after 70 days. However, it cannot be expected that these data approximate the elastic portion of the total deformation, which might be recoverable upon removal of the load.

Recovery Behavior

The loads were removed after 70 days, and the recoverable creep was measured after 2 years of storage at 80°F (table 4). Adhesive A exhibited the highest creep recovery of all adhesives tested: 96 to 100 percent for specimens which had been previously loaded at 80°F, and 72 to 80 percent for specimens previously loaded at 120°F.

In most adhesives, creep recovery was greater in joints exposed to the lower stress levels in dead loading. Adhesives C, E, K, and V had good recovery only at 80°F and at the lowest levels of stress. In no instance did adhesive B recover more than 70 percent of the total slip. The creep recovery at 80°F of all adhesives, with the exception of adhesive A, was much less in specimens loaded under 120°F compared to specimens loaded under 80°F. In the case of specimens at 120°F dead loaded, recovery would have been greater had it also taken place at 120°F[5]. Of course, this argument is not applicable to joints of adhesives E and K that failed at the higher stress levels.

Creep Modulus

Engineering formulae for predicting short-term deformations and strength of a composite make use of shear modulus and static shear strength values of adhesive layers. In the case of viscoelastic adhesives, time-dependent behavior of the adhesive significantly affects the performance of the composite which it bonds. The concept of substituting a creep modulus for shear modulus in the elementary engineering design formulae has been practiced by the plastics industry for some time.[6] Although the concept of creep modulus is a gross simplification of extremely complex material behavior, it has proved useful (1) for comparing materials, (2) for designing of fabricated parts, (3) for characterizing plastics for long-term performance, and (4) for specification purposes *(2).*

Figures 6 through 8 show the stress-time-modulus relationship of three types of elastomer-based adhesives at 80°F. Plots of adhesive behavior such as this allow the designer to determine the adhesive's resistance to deformation at the anticipated service conditions. In the following discussion, we have selected portions of these three-dimensional plots to show how creep modulus varies with temperature, stress level, and adhesive formulation. as well as time.

Figures 9 through 11 illustrate the response of three of the construction adhesives to time, temperature, and stress level. (Other important factors not explored in this study are the conditions of glueline formation and humidity levels during loading and recovery.) Figure 9 illustrates the three types of behavior found in this study of six construction adhesives. Creep modulus at the highest and lowest stress levels for each adhesive is shown as a function of time at 80°F.

The creep modulus of adhesive C was time-sensitive at the 40 Ibf/in.^{2} stress level. But at the high stress level, the creep modulus of adhesive C was virtually independent of time after the first 100 minutes under load. This may be indication of a creep limit which is a constant value approached asymptotically with increasing time (see fig. 9). If so, adhesive C may have a useful creep modulus at 80°F of about 60 Ibf/in.^{2}. The minimum creep modulus is still dependent upon the temperature, although apparently Independent of the time (fig. 11).

The creep modulus of adhesive A (fig. 9) is essentially independent of time in the first 1,000 minutes under load. Time dependence appears to increase after 1,000 minutes at the lower stress level, but is not really evident for the 80 Ibf/in.^{2}. At both stress levels the creep

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[5] Had recovery been allowed to take place at 120°F, the temperature at which creep took place, more complete recovery might be expected. Recovery in response to elastic elements in the viscoelastic model is slowed by viscous elements of the model. Viscosity increasing with decrease in temperature will increase recovery time.

[6] A forerunner to ASTM D-2990 *(2),* ASTM D-674 was originally published as a recommended practice in 1956.

modulus appears heading eventually to zero. More evidence of this trend can be identified in figures 10 and 11.

The creep modulus of adhesive K is extremely time sensitive at the stress levels used in this study. The modulus decreased from > 2,000 lbf/in.^{2} at 10 minutes load duration to < 500 lbf/in.^{2} after 1,000 minutes (fig. 9). Although it is poorly defined at the shorter times due to the small deformations, there appears to be little difference in creep modulus due to the level of stress.

The creep behavior of adhesives E and K (with the exception of fig. 9) is neglected because of the great number of failures of these adhesives under load, and the difficulty associated with reading the very small deformations observed at short times. It may be rather incongruous to speak of the great number of failures and the many small deformations at the same time, but adhesives E and K, as mentioned, are quite rigid during short-term loading yet very sensitive to long-term loading.

Figure 10 illustrates the effect of temperature upon the creep modulus, after 70 days of dead load, for adhesives A and C (the behavior of adhesives B and V is similar to that shown for adhesive C). Neither adhesive E nor K would support a load at 120° or 160°F for more than several hundred minutes. These results agree with previously published results *(8)* with these same adhesives. The earlier study showed that adhesives B, C, and V were able to withstand a 2 lbf/in.^{2} load during rapid heating to temperatures exceeding the char temperature of wood. On the other hand, adhesives E and K failed at about 200°F and were not heat resistant. Adhesive A behavior was intermediate.

The difference in the responses of adhesives C and A to increased temperature noted above is immediately evident (fig. 10). Adhesive C creep modulus is quite sensitive to temperature increase from 80° to 120°F while the creep modulus of adhesive A is relatively insensitive. Conversely, the creep modulus of adhesive C becomes quite insensitive to temperature from 120° to 160°F, while adhesive A creep modulus becomes increasingly so. In fact, an extrapolation of the curves for adhesive A, indicates zero creep modulus after 70 days of dead load at 165°-175°F.

In figure 11, the creep modulus at 70 days is shown as a function of the level of stress imposed on the joint. The response of adhesives A and C at three temperatures is markedly different. Between the 40 and 160 lbf/in.^{2} stress levels at 80°F, the creep modulus of adhesive C decreases with increasing stress which is indicative of viscoelastic behavior. But above 160 lbf/in.^{2} at 80°F, the modulus becomes constant. On the other hand, at 120° and 160°F, the creep modulus is constant until the highest stress level is reached, when it becomes a decreasing function of the stress. The horizontal, linear portions of these curves represent elastic response of the adhesive to stress. For design purposes, it might be useful to draw a temperature-stress envelope of the elastic region of response (see fig. 11), giving designers ranges of stress level and temperature with which to work.

The creep modulus of adhesive A is stress dependent throughout most of the range of stress levels and temperatures studied. Only at the lowest stress levels of the 120° and 160°F curves is there any sign of elastic behavior after 70 days under load. The 80°F curve and most of the 120°F curve are linearly decreasing functions of stress. This would seem to indicate purely viscous behavior, and yet this particular adhesive obviously recovered better after unloading than did adhesive C.

As before, the behavior of adhesives B and V was similar to adhesive C behavior. Data for adhesives E and K was available only at 80°F. The creep moduli at that temperature were also linearly decreasing functions of stress, similar to adhesive A at 80°F.

Conclusions and Implications for Adhesive Use

All the construction adhesives in this study were sensitive to temperature in their response to load. As temperature increased, strain at a given time increased and the corresponding creep modulus decreased. Shear slip of the polyvinyl acetate adhesive could not be detected at any temperature under the low humidity conditions used in this study.

Internal factors-such as the type and amount of fillers, plasticizers, and intermolecular bonding or entanglement-also influence the creep and recovery behavior of adhesives. These factors alone provide an almost infinite variety of adhesive behavior, but in a general sense the adhesives in this study exhibited three types of behavior (fig. 12):

I. Small strain upon initial loading, followed by extensive strain under prolonged loading but with good recovery after unloading.

II. Large strain upon initial loading, followed by slow but extensive strain under prolonged load and good recovery after unloading.

III. Very small strain upon initial loading, followed by extensive strain under prolonged load, with strain rate accelerating until failure.

Adhesives of type I or type II behavior appear to have a creep limit under moderate load and environmental conditions. If a creep limit exists, then a long-term strength and creep modulus may be determined for use in design. More extensive investigation, including the effects of longer load times and of moisture, is required before a creep limit can be said to exist for any adhesive. Adhesives exhibiting type III behavior may also have a creep limit at very low load levels and mild environmental conditions, but this appears unlikely.

Most construction adhesives on the market today will exhibit type III behavior, because they have been designed for gap-filling ability and for resistance to short-term or live-load applications. Adhesives for this large market have been carefully formulated to provide these properties in the most cost-effective manner. The fact that they exhibit type III behavior is not a detriment to their intended use. On the other hand, this research indicates there are construction adhesives on the market (although generally more expensive than type III adhesives) that have long-term properties that designers may be able to utilize.

Summary

This study evaluated the time-dependent strain behavior of construction adhesives at three temperatures and five stress levels. The duration of load at each temperature was 70 days. Shear slip determinations were made at 10, 100, 1,000, 10,000, and 100,000 minutes (70 days) using a linear traveling microscope. Better resolution, more readings between 10,000 and 100,000 minutes, and better environmental control are desirable for future studies.

Six construction adhesives and one polyvinyl resin emulsion adhesive were studied. Three construction adhesives appear unsuitable for dead loading. They either failed or were near failure at the end of the tests. The other three construction adhesives showed feasibility for dead-load applications. While the creep modulus is a small fraction of the short-term shear modulus, the data of this study seem to indicate that the creep moduli of some adhesives approach a limit greater than zero. The limit was not dependent on the stress level within the range used in this study, but it was dependent on the temperature. The polyvinyl resin emulsion adhesive did not deform enough to be resolved under the test conditions of this study. For this adhesive, moisture is more critical than temperature within the range of temperatures and stress levels used. Moisture level was very low throughout these exposures.

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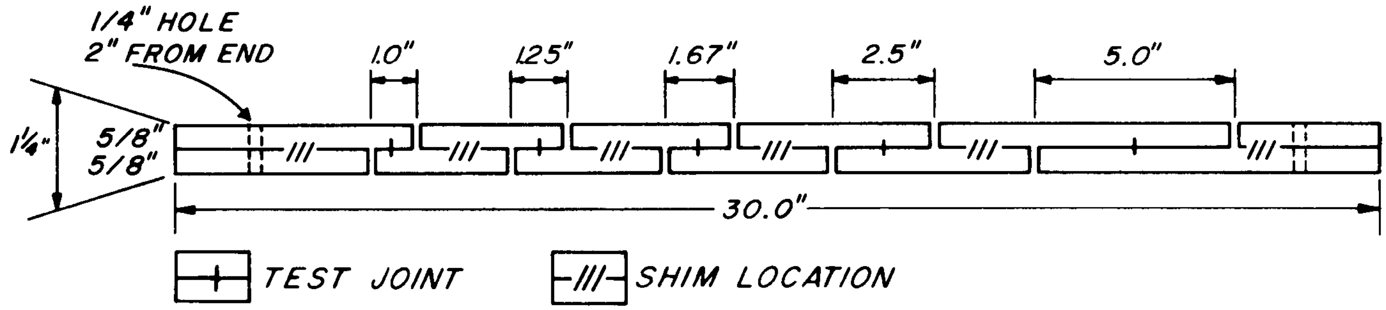

Figure 1.–Test specimen side view showing the position of shims for controlling glueline thickness and the location of saw kerfs to form the five shear test areas.

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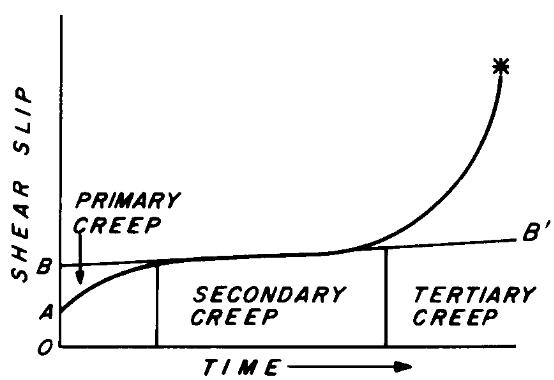

Figure 2.–Components of a typical creep response for a material exhibiting viscoelastic-plastic deformation.

(M 149 409)

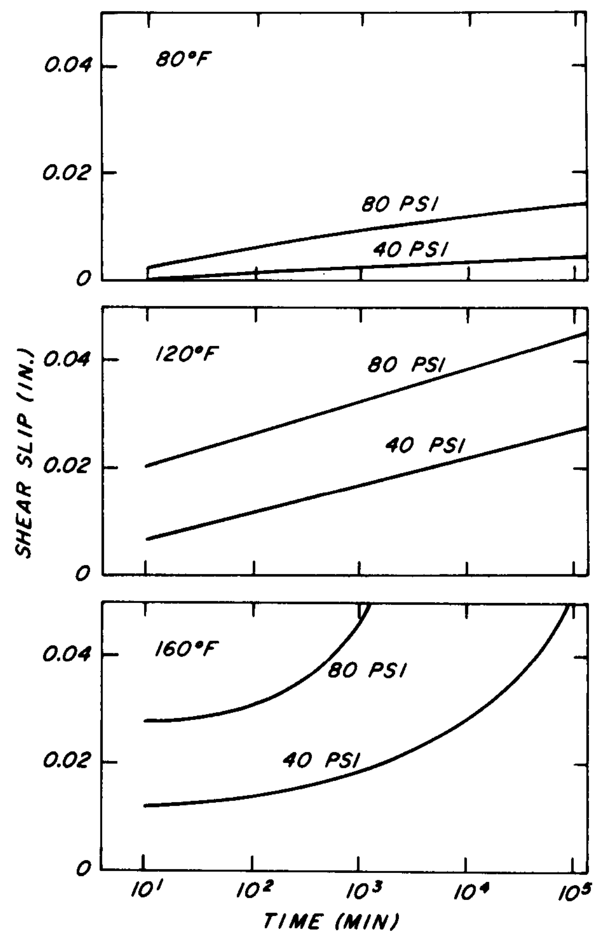

Figure 3.–Shear slip vs. time for adhesive C at three temperatures and two stress levels.

(M 149 410)

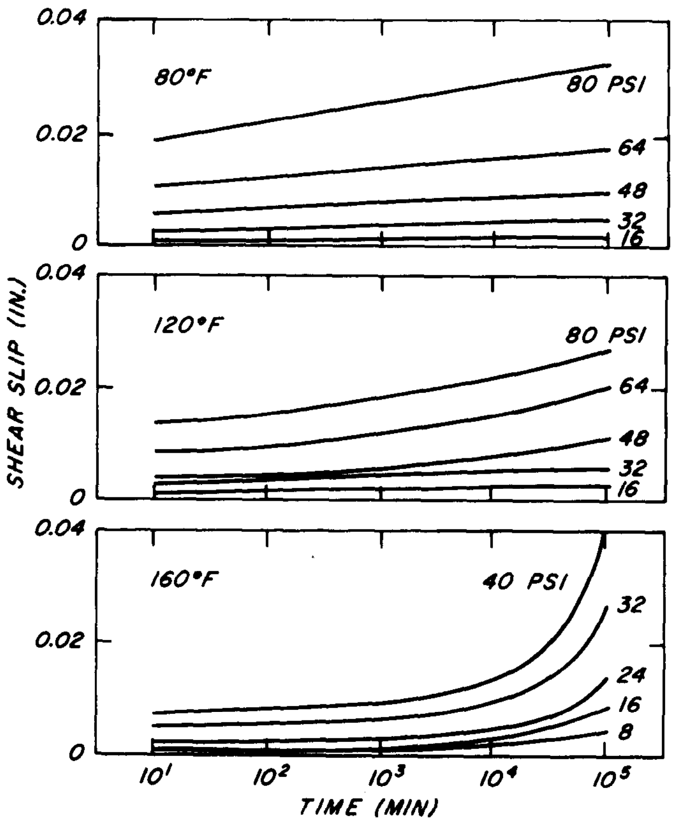

Figure 4.–Shear slip vs. time for adhesive A at three temperatures and five stress levels.

(M 149 411)

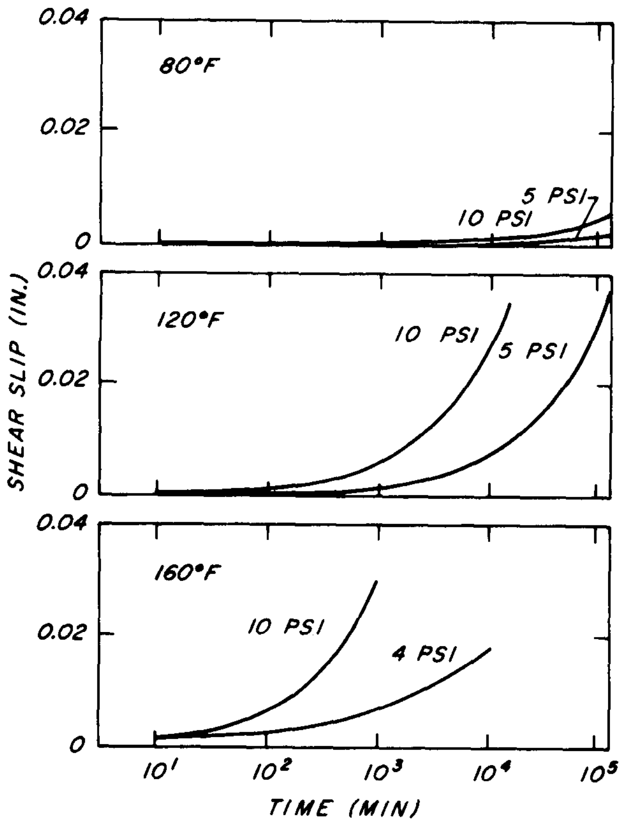

Figure 5.–Shear slip vs. time for adhesive K at three temperatures and two stress levels.

(M 149 412)

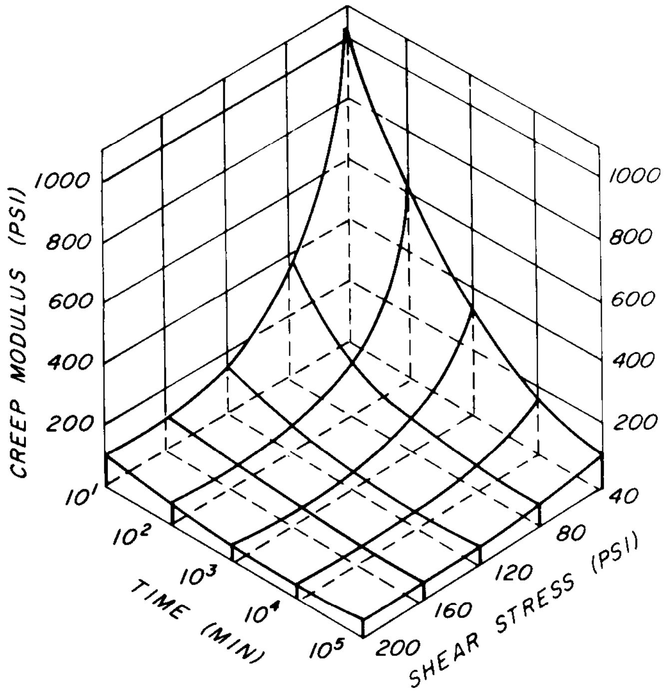

Figure 5.–Creep modulus of adhesive C as a function of stress and time at 80°F.

(M 149 413)

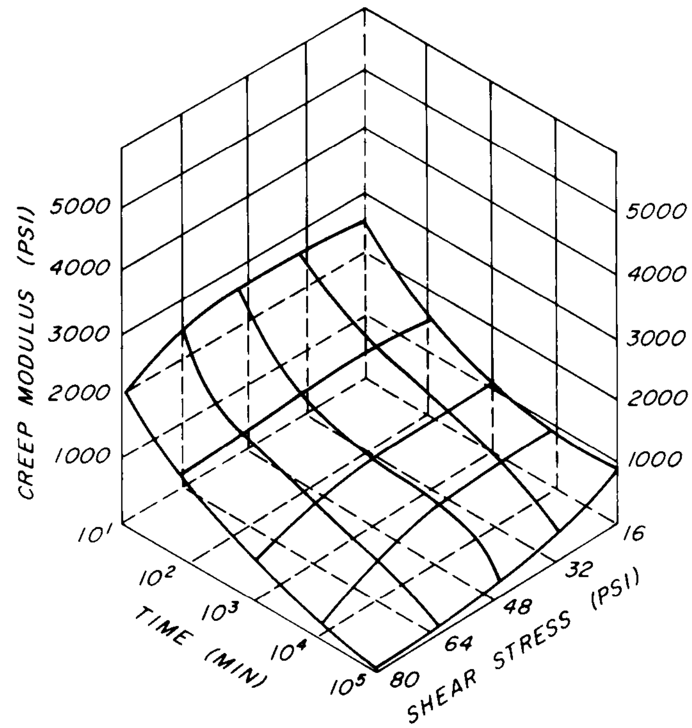

Figure 8.–Creep modulus of adhesive E as a function of stress and time at 80°F.

(M 149 414)

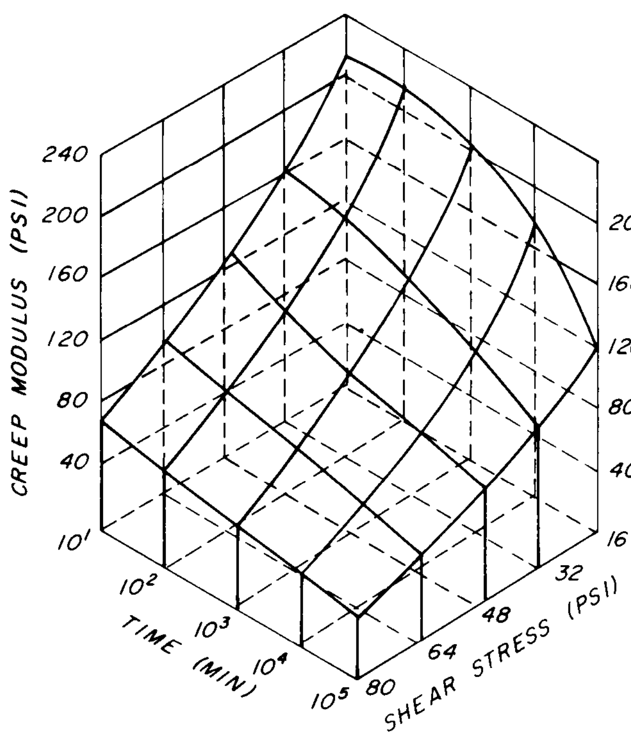

Figure 7.–Creep modulus of adhesive A as a function of stress and time at 80°F.

(M 149 415)

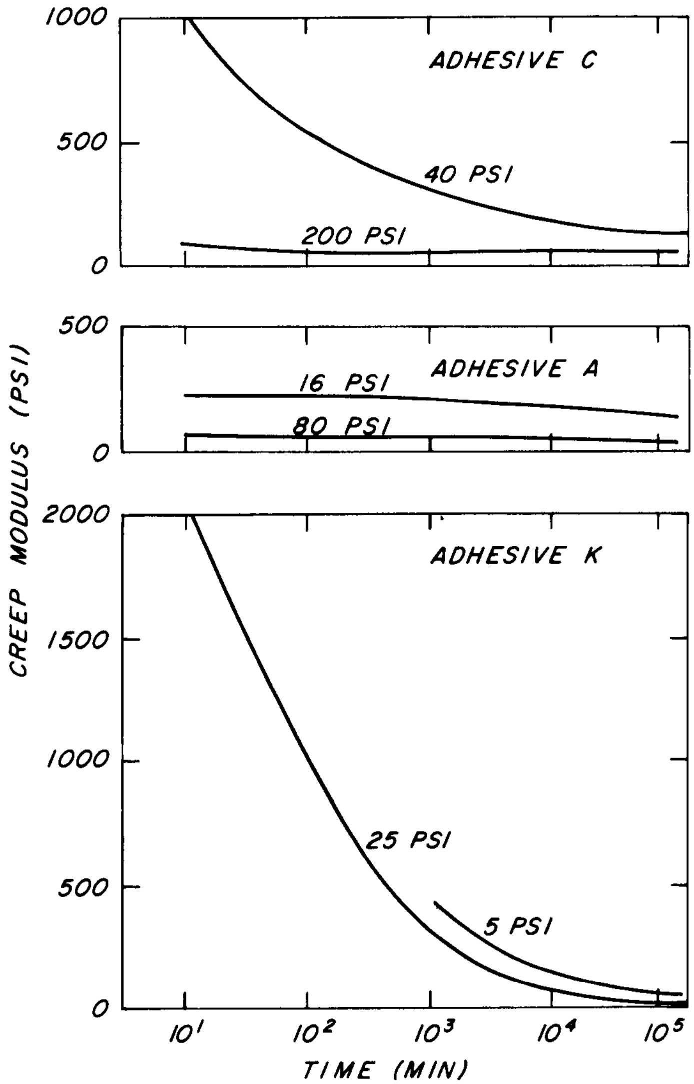

Figure 9.–The dependence of creep-modulus upon time at two stress levels at 80°F.

(M 149 416)

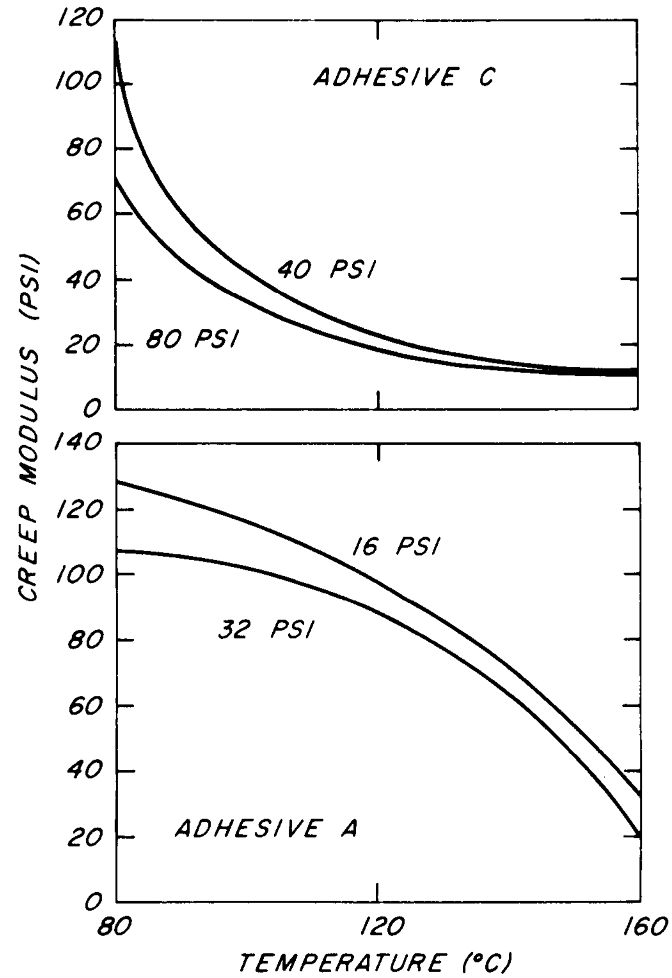

Figure 10.–The dependence of creep modulus on temperature at two stress levels, after 70 days under load.

(M 149 417)

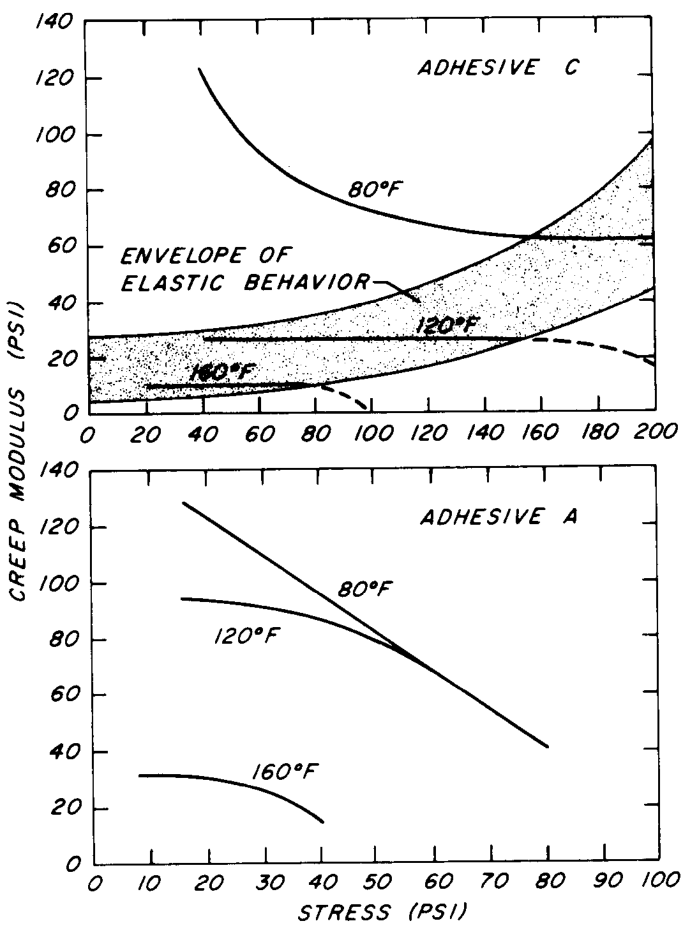

Figure 11.–The dependence of creep modulus on stress at three temperature levels, after 70 days under load.

(M 149 418)

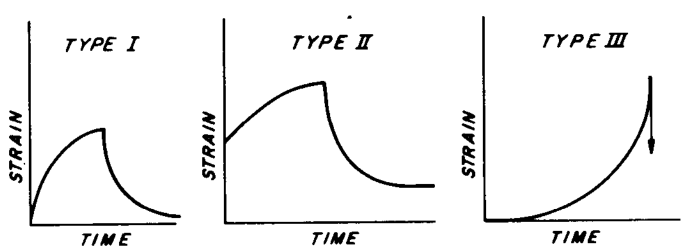

Figure 12.–Three generalized types of adhesive strain response to an applied load with time.

(M 149 419)

Table 1.–Shear stress applied to test joints

Adhesive	Temperature while under load	Shear stress at 1.0 in.² joint area	1.25 in.² joint area	1.67 in.² joint area	2.5 in.² joint area	5.0 in.² joint area
	°F	Lbf/in.²				
A	80	80	64	48	32	16
	120	80	64	48	32	16
	160	40	32	24	16	8
B	80	200	160	120	80	40
	120	200	160	120	80	40
	160	100	80	60	40	20
C	80	200	160	120	80	40
	120	200	160	120	80	40
	160	100	80	60	40	20
E	80	80	64	48	32	16
	120	80	64	48	32	16
	160	40	32	24	16	8
K	80	25	20	15	10	5
	120	25	20	15	10	5
	160	10	8	6	4	2
V	80	100	80	60	40	20
	120	100	80	60	40	20
	160	50	40	30	20	10
EE	80	200	160	120	80	40
	120	200	160	120	80	40
	160	100	80	60	40	20

Table 2.–Total bondline slip after 70 days of dead load

Adhesive	Temperature while under load	Maximum stress	Bondline slip[1] 100 Percent maximum stress	80 Percent maximum stress	60 Percent maximum stress	40 Percent maximum stress	20 Percent maximum stress
	°F	Lbf/in.²	10^{-3} in.				
A	80	80	33	18	10	5	2
	120	80	32	21	10	6	3
	160	40	40	27	14	8	4
B	80	200	45	29	27	16	4
	120	200	79	84	64	42	28
	160	100	F	F	89	50	19
C	80	200	45	28	26	14	4
	120	200	F	87	67	45	28
	160	100	F	F	85	55	26
E	80	80	18	11	3	1	0
	120	80	F	F	F	F	F
	160	40	F	F	F	F	F
K	80	25	33	22	9	6	2
	120	25	F	F	F	F	36
	160	10	F	F	F	F	55
V	80	100	45	33	26	18	8
	120	100	F	F	47	34	22
	160	50	F	F	48	29	16

[1] F indicates two or more of the four specimens exposed failed under dead load.

Table 3.–Bondline slip 10 minutes after loading

Adhesive	Temperature while under load	Maximum stress	Initial bondline slip relative to total slip at				
			100 Percent maximum stress	80 Percent maximum stress	60 Percent maximum stress	40 Percent maximum stress	20 Percent maximum stress
	°F	Lbf/in.^{2}	Pct				
A	80	80	60	60	55	60	60
	120	80	45	45	45	50	40
B	80	200	55	60	20	15	20
	120	200	50	45	40	35	20
C	80	200	60	50	35	20	10
	120	200	50	45	45	45	25
E	80	80	<1	<1	<1	0	0
	120	80	<1	<1	<1	<1	<1
K	80	25	1	2	2	2	0
	120	25	<1	<1	<1	<1	<1
V	80	100	50	40	35	35	20
	120	100	[1]--	[1]--	40	40	25

[1] Specimen failed-no estimate of slip at failure.

Table 4.–Percent of total slip recovered 2 years after unloading[1]

Adhesive	Temperature while under load	Maximum stress	Recoverable slip at				
			100 Percent maximum stress	80 Percent maximum stress	60 Percent maximum stress	40 Percent maximum stress	20 Percent maximum stress
	°F	Lbf/in.^{2}	Pct				
A	80	75	97	96	99	100	100
	120	75	76	72	75	83	89
B	80	200	55	41	52	50	63
	120	200	13	13	14	10	20
C	80	200	46	41	46	49	73
	120	200	0	22	30	17	23
E	80	75	18	31	44	97	100
	120	75	0	0	0	0	0
K	80	25	32	46	38	41	90
	120	25	0	0	0	20	14
V	80	123	66	64	69	77	92
	120	123	0	0	42	34	42

[1] Recovery took place at ambient laboratory conditions ≅80°F.

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