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Load-Strain Properties and Splitting of Roof Membranes

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ABSTRACT: The load-strain properties of several bituminous membranes when tested in tension are examined and the effect of temperature on the breaking load, load-strain modulus, and breaking strain is considered. The shear properties of the bitumens used as adhesives in the production of the membranes are examined at temperatures from −15 F (−26 C) to 32 F (0 C) at a rate of shear of 0.21 per min. The observed transition in the shear modulus of the asphaltic material at 0 F (−18 C) is found to coincide with the glass transition temperature of this material. The development of a critical-thickness concept is described, and it is suggested that the performance of roofing membranes under deformation may be controlled by the load-strain properties of the membrane and the shear properties of the adhesive.

KEY WORDS: bitumens, roofing membrane, tensile strength, shear testing, glass transition temperature

Asphalt and coal-tar-pitch built-up roofings are used in many countries and particularly in North America to protect large buildings that have relatively flat roofs. These roofing systems are exposed to various climatic conditions ranging widely, not only with location but also with the season. Because of premature failure of components of the systems, the expected life of 20 years or more is not always obtained. The mode of failure varies depending on the conditions of application and service of the roof system. There are in general three types of failures of built-up roofing membranes: blistering, splitting, and wrinkling or ridging. Several authors [*1–7*][2] have examined these types of failures and their extent; their studies have emphasized the interdependence and interaction between components of the roofing system.

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

In recent years, the type of failure of roofing systems in northern climates has often been one of splitting. This prompted this present study which is a continuation of previously reported work [*8*]. Improved techniques in the preparation and load-strain testing of conventional bituminous membranes are reported, together with some results obtained for a variety of materials and temperature conditions. Some results on the shear properties of the bitumens used in this study are reported, and their possible significance under certain conditions is discussed.

TABLE 1—*Materials used in preparation of load-strain specimens.*

Material	CSA Specification
Asphalt, 140 F softening point (Venezuelan)	A 123-7 (1953) Type 1
Coal-tar pitch, 140 F softening point	A 123-13 (1953) Type A
Asphalt-saturated organic felt	A 123-6 (1953) 15-lb Type
Asphalt-saturated asbestos felt	A 123-9 (1953)
Asphalt-impregnated glass felt	A 123-17 (1963) Type 1
Coal-tar pitch–saturated organic felt	A 123-8 (1953) 15-lb Type
Coal-tar pitch–saturated asbestos felt	A 123-10 (1953)

TABLE 2—*Thickness of spacers required in the press method of preparing built-up roof membranes.*

Material	Spacer Thickness, in.			Bitumen-Pouring Temperature, deg F
	2 Ply	3 Ply	4 Ply	
Asphalt-organic	0.085	0.140	0.195	325
Asphalt-asbestos	0.073	0.125	0.170	325
Asphalt-glass	0.103	0.158	0.213	325
Coal-tar pitch–organic	0.095	0.150	0.205	270
Coal-tar pitch–asbestos	0.095	0.150	0.205	270

Materials and Testing Procedure for Load-Strain Properties of Membranes

Load-strain measurements were obtained from membranes composed of five types of bitumen-saturated or impregnated felts combined with one of two types of bitumens. The materials that were used complied with specifications of the Canadian Standards Association; the materials are listed in Table 1. Specimens of two, three, and four plies of felt adhered with the selected bitumen were prepared using bitumen at a rate of 25 lb per 100 ft^2. The specimens were prepared by heating the bitumen to about 300 F (149 C) and pouring it over a sheet of bitumen-saturated or impregnated felt placed over a release paper composed of silicone-treated aluminum foil. A sandwich was formed with a second sheet of felt and a second release paper placed over this. The sandwich was placed in a laboratory press heated to about 190 F (88 C). Spacers were used to control the thickness of the bitumen during the pressing operation; the total thickness of these spacers depended upon the nature of the felts and the number of plies. Table 2 gives some details of specimen preparation. Figure 1 shows the method of membrane preparation which was repeated until the required number of plies was obtained.

The final tensile specimen was cut from the membrane using a die with dimensions shown in Fig. 2. Specimens were prepared with the fibers oriented along the direction of testing (machine direction) and perpendicular to the direction of testing (cross direction). The load-strain properties were measured on five samples of each membrane at temperatures of −40 F (−40 C), −15 F (−26 C), 0 F (−18 C), 32 F (0 C), and 77 F (25 C). The values at −40 F were determined in a tensile testing machine equipped with a temperature chamber that controlled the specimen temperature within ±2 F (±1.1 C) during the test. All other values were obtained using a horizontal-type tensile testing apparatus as previously described [*8*]. The apparatus was placed in a cold room in which the temperature was maintained during the test within ±2 F (±1.1 C) of the selected test temperature. All values were obtained with a head movement of 0.050 in./min, which represents a rate of strain of 1.1 per cent

FIG. 1—*Press method of preparing built-up roofing membranes.*

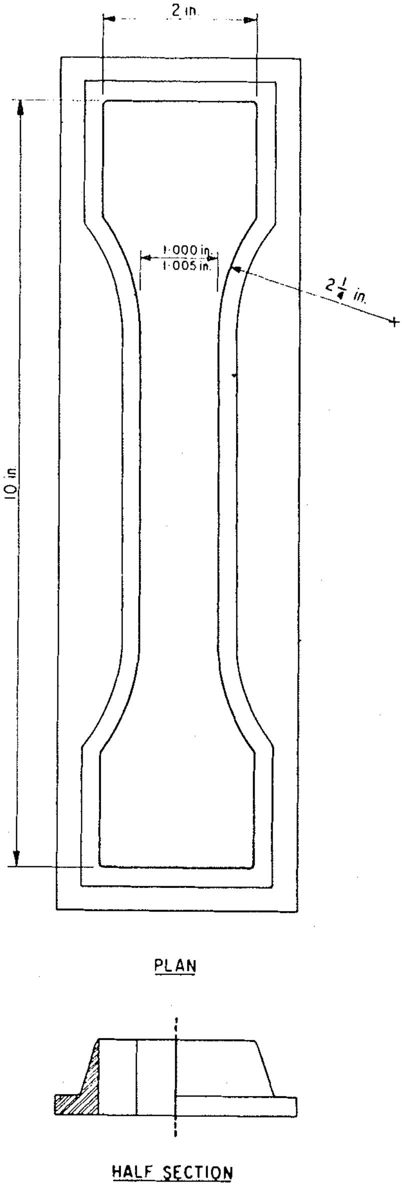

FIG. 2—*Die for cutting tension specimens of built-up roofing membranes.*

per minute over the parallel portion of the sample. For all other temperatures other than −40 F (−40 C), the strain was measured with a strain gage 2 in. in length which was placed in this parallel section. At −40 F the strain was measured as the deformation between the jaws which were 7 in. apart at the start of the test. In this case, the rate of strain was 0.7 per cent per minute.

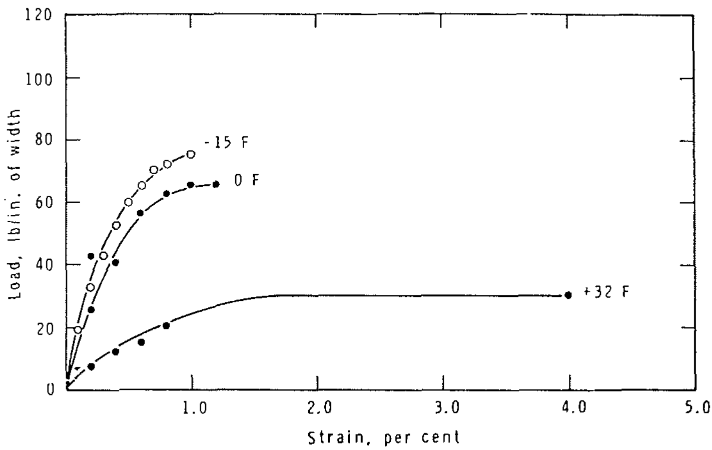

FIG. 3—*Load-strain curve of two-ply asphalt-asbestos membranes in cross-machine direction.*

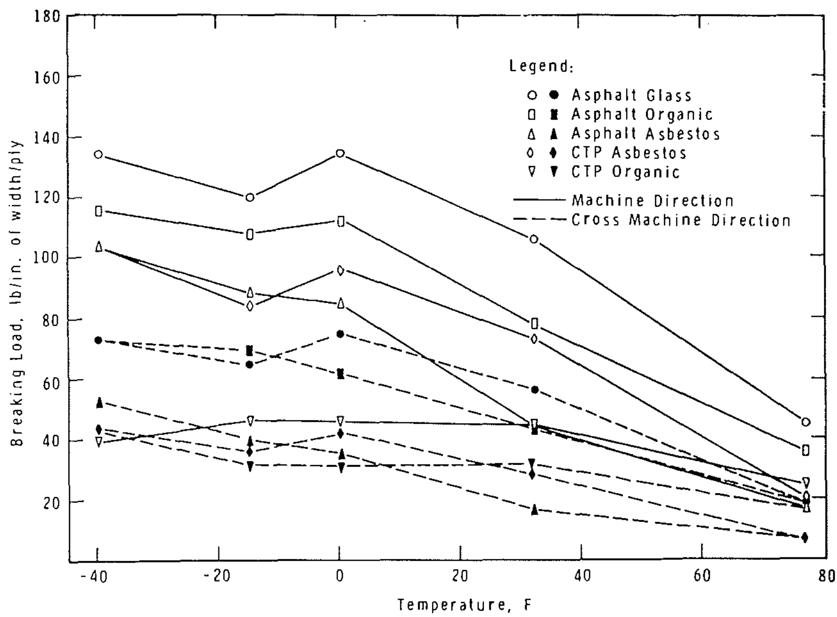

FIG. 4—*Effect of temperature on the breaking load of roofing membranes.*

Measurements were made of the breaking strain expressed as a percentage, the breaking load, *F*, expressed in pounds per inch of width, and the load-strain modulus expressed in pounds per inch of width. This load-strain modulus was obtained from the slope of the initial tangent to the load-strain curve and may be considered to be the elastic modulus, *E*, multiplied by the thickness of the membrane, T_R. A load-strain curve

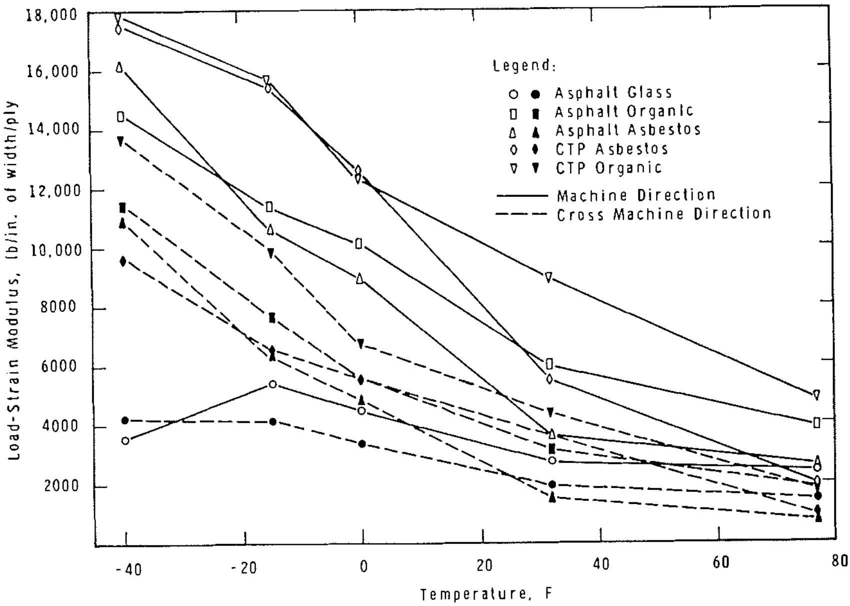

FIG. 5—*Effect of temperature on the load-strain modulus of roofing membranes.*

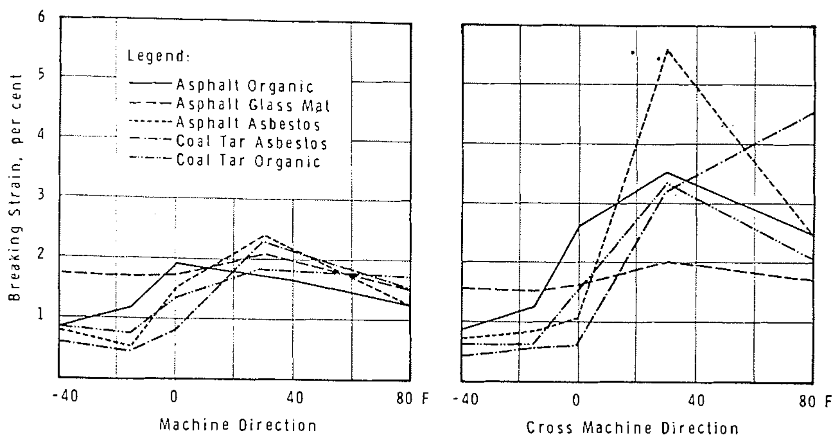

FIG. 6—*Effect of temperature on the breaking strain of roofing membranes.*

is shown in Fig. 3. It was found that the breaking load, F, and the load-strain modulus, $E \cdot T_R$, could be expressed as values per ply and that actual values of two, three, and four plies were simple multiples of these values. The values of the breaking load per ply for the various temperatures are shown in Fig. 4. In Fig. 5 the values of the load-strain modulus per ply are shown for the various temperatures; Fig. 6 indicates the values of the breaking strain at the various temperatures. The values shown in

Fig. 6 are the average values of the breaking strains of the two-, three-, and four-ply materials at the various temperatures.

Measurement of Shear Properties of Bitumens

The shear strength and shear modulus of the two bitumens used in the load-strain studies were measured at temperatures of −15 F (−26 C), 0 F (−18 C), 5 F (−15 C), 13 F (−11 C), 22 F (−6 C), and 32 F (0 C). A pad of bitumen 0.25 in. thick was placed in a simple shear apparatus which was devised for the purpose. The unit was placed in the laboratory

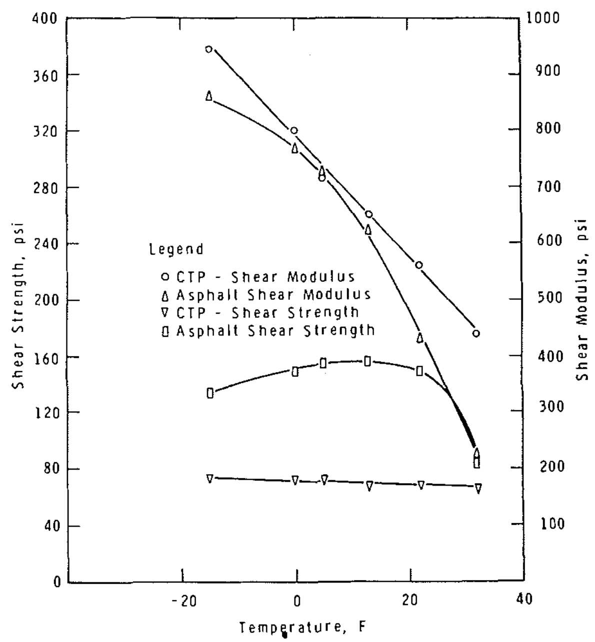

FIG. 7—*Effect of temperature on shear properties of bitumens.*

press and heated to obtain a bond between the metal component of the apparatus and the bitumen. The apparatus was then placed in a horizontal-type tensometer [*8*] and tested until failure, at a rate of shear strain of 0.21 per minute. Five determinations were made of each bitumen at the various temperatures, and, from these measurements, values of the shear strength of the bitumen and the modulus at maximum shear were obtained (Fig. 7).

The results of the shear measurements indicate that for coal-tar pitch a linear relationship exists between the measured shear properties and the temperature under the conditions tested. The asphalt sample, on the other hand, indicates that a transition in properties takes place in the region of 0 F. To explore this further, the asphalt and coal-tar-pitch samples were subjected to differential thermal analysis in an atmosphere of nitrogen. About 25 mg of bitumen was used and heated in an atmosphere of nitrogen at a rate of 36 F (20 C) per minute from −148 F to +212 F (−100 to +100 C). It was found that the asphalt had a second-order transition or glass transition temperature of −0.4 F (−18 C) and the coal-tar pitch had a transition at +51.8 F (+11 C). Wada and Hirose [9] found that, above the glass transition temperature, asphalts are viscoelastic. The Fraass brittle-point temperature was also examined, using a modified unit [10]. The asphalt had a value of −5 F (−20.5 C) and the coal-tar pitch a value of +51 F (+10.6 C). These studies indicate that a change in the physical properties of the asphalt would be expected at about 0 F and with the coal-tar pitch at about 52 F.

Discussion

The results of the load-strain studies on the membranes indicate a general increase in the breaking load and load-strain modulus with a decrease in temperature. The breaking strain with most membranes decreases with decreasing temperature. The amount of decrease of the breaking strain and increase in breaking load and modulus varies with the type of membrane and the orientation of the fibers used as reinforcing material in the membrane.

If rupture or splitting of roof membranes is to take place, then the deformation at a point must be greater than the breaking strain of the membrane at that location. This deformation may be caused by thermal changes, moisture changes, or movements in the substrate. Studies by Cullen [3] on the thermal coefficient of expansion of bituminous membranes have indicated that from a 60 F temperature change from +30 to −30 F strains of 0.07 to 0.18 per cent would be developed on a sample that is uniformly deformed. These values are about 10 to 20 per cent of the breaking strains shown in Fig. 6. They indicate, as has already been proposed by Cullen and others, that uniform contractions due to reduction in temperature will not produce tensile failure in the membrane.

The apparent margin of safety of from 5 to 10 times shown by these results is predicated on the following assumptions: that Cullen's values of thermal contraction apply to these materials; that thermal contraction is the only strain-producing effect; and that the laboratory values of limiting tensile strains are representative of materials in service. Consideration of rates of loading as between the laboratory and real situations leads to the conclusion that the laboratory values of breaking strain may be conservative. On the other hand, membranes in service may exhibit reduced breaking strains as a result of possible internal stresses or reduction in strength resulting from actual weathering conditions. They are also usually stressed in two directions, whereas the laboratory tests involved unidirectional loading.

There must be some further reservation about the possibility that, as a result of moisture conditions in practice, the contractions developed may be greater than those predicted from the limited range of conditions explored to date in the laboratory. The possibility of a uniform expansion of the deck or other substrate over the whole of the roof area leading to strains in excess of the limiting tensile strain for the membrane can be ruled out, since a roof capable of such over-all dimensional changes would normally be quite unacceptable.

In the absence of confirmation of such effects, it is reasonable to accept, with the reservations noted, the tentative conclusion that uniformly developed contractions in membranes should not lead to tensile failure or splitting. This situation then forces serious consideration of the ways in which nonuniform strains in excess of the membrane breaking strains might be produced. The development of such nonuniformity can only arise as a result of nonuniform movements in the substrate which are transmitted to the membrane through shear forces in the adhesive. The most obvious case is that of a membrane bonded to a deck that has a crack or joint that opens. In this case, the movement at the joint may induce large local strains in the membrane, on either side of the joint, through opposing shear forces in the adhesive.

The work of Koike [*11*] has relevance to the case of induced nonuniform strains in the membrane. He has considered the influence of the shear properties of the adhesive as well as the properties of the membrane and has proposed that, depending on the balance between these, failure may occur by rupture of the membrane or by shear in the adhesive. The criterion which he has developed states that failure will be by rupture of the membrane when

$$T_B \geqq F\left(\frac{G}{E \cdot T_R \cdot T_a}\right)^{1/2}$$

where:

T_B = shear strength of bituminous adhesive,
G = shear modulus of bituminous adhesive,
F = tensile strength of roofing membrane,
$E \cdot T_R$ = load-strain modulus of roofing membrane, and
T_a = thickness of bituminous adhesive.

But if

$$T_B < F\left(\frac{G}{E \cdot T_R \cdot T_a}\right)^{1/2}$$

failure will be by shear of the adhesive.

The transition from shear failure of the adhesive to rupture failure of the membrane thus is shown to be influenced by the thickness of the adhesive. Above a certain value of this adhesive thickness, the membrane will fail by tensile rupture; below this value, the failure will be by shear failure of the adhesive. The value of this critical thickness will depend upon the nature of the membrane and adhesive, the direction of its reinforcing, and the temperature.

A difficulty arises in applying Koike's criterion to real membranes. He has assumed ideal materials exhibiting stress-strain linearity up to failure, with properties which are independent of temperature. These conditions are not satisfied by real membranes in situations in which the movements arise from reduction in temperature. They are more nearly realized in the case of a membrane which is loaded at a constant low temperature.

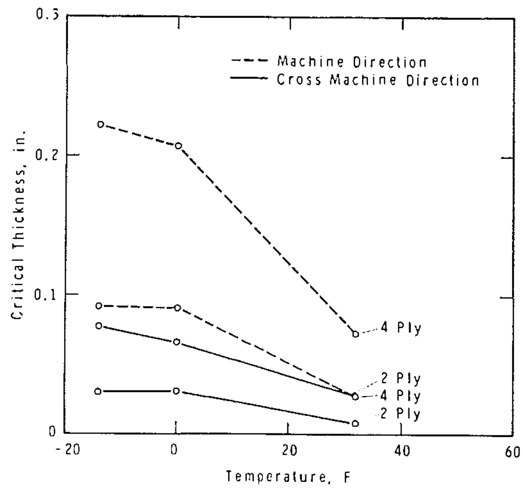

FIG. 8—*Critical thickness values of bituminous adhesives of asphalt-asbestos membranes.*

Using Koike's criterion and the values of the tensile properties of the membrane and shear properties of the adhesive that are now reported, the calculated values of the critical thickness of four-ply membranes at −15 F varies from 0.071 to 0.72 in., depending upon the nature of the bitumen and upon the nature and direction of the reinforcing fiber. Figure 8 illustrates the effect of temperature on the values of the critical thickness of some asphalt-asbestos membranes.

A further step was taken to obtain direct experimental evidence of the mode of failure. A two-ply asphalt-asbestos membrane specimen taken from the cross-machine direction, 2 in. wide by 7½ in. long, was bonded across the joint between two adjacent aluminum plates ½ in. in thickness. The asphalt that was used as the adhesive to prepare the membrane was also used as the bonding bitumen (0.020 in. thick) between the membrane and the aluminum plates. The plates were then pulled apart in a

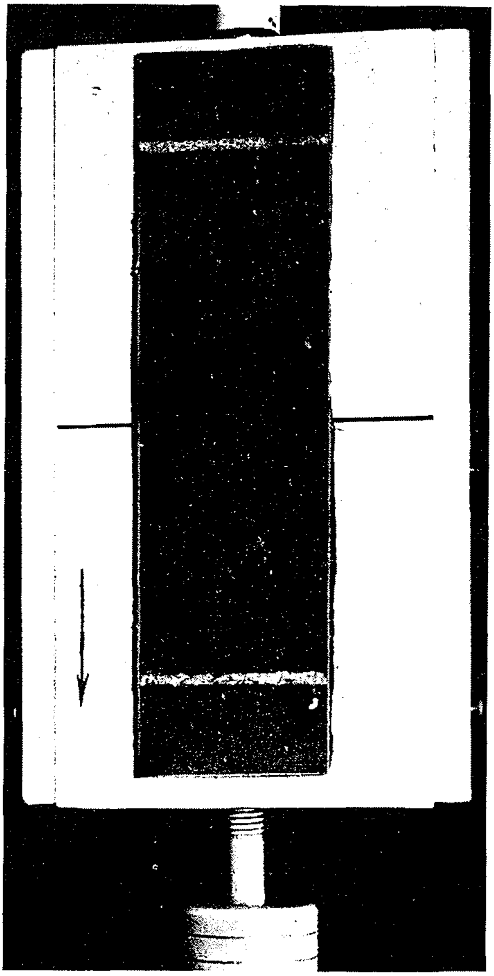

FIG. 9—*Rupture failure of bituminous membranes using an adhesive with a thickness greater than the critical thickness.*

tensile testing machine at a head speed of 0.005 in./min at a temperature of −15 F. Under this condition of test, the adhesive (thickness 0.020 in.) failed by shear failure on each of three separate experiments.

When the same type of membrane was tested in the same way with a bonding bitumen 0.042 in. thick, the membrane failed in rupture (Fig. 9). This type of failure occurred on each of three separate experiments with this thickness of adhesive after a slight amount of shear of the adhesive in the immediate area of the joint. This sample was pulled apart at a head speed of 0.010 in./min.

This experiment and Koike's criteria apply to the case of a membrane bonded to a rigid substrate in which there is a crack or joint that opens.

Consideration must be given to other cases, such as the nonuniform strain that is developed when the membrane is bonded to insulation in board or sheet form capable of undergoing substantial shrinkage and of sufficient strength and stiffness to induce large strains in the membrane over joints between boards. In this case the forces must also be transferred to the membrane by opposing sets of shear forces in the adhesive. Under these conditions the criteria of Koike and the experimental results suggest that in this second case there may be a change in the mode of failure with variation in adhesive thickness.

Conclusions

A knowledge of the performance of roofing membranes under tensile deformation is necessary for an adequate understanding of the performance of these materials in service. The present studies indicate that variations exist in the load-strain properties of membranes of different compositions. The tensile breaking load and the load-strain modulus of the roofing membranes increase with a decrease in the temperature at which these parameters were measured. The breaking strain of many of the membranes decreases with a decrease in temperature, but even at very low temperatures (−40 F) the value of this breaking strain is still 0.8 to 2.0 per cent.

If the reported values of thermal-expansion coefficients are applicable to the materials examined, if these values are not significantly increased with aging and the effect of moisture, and if the measured tensile properties are representative of service conditions, there is no reason to believe that uniformly developed contractions in membranes can lead to tensile failures or splitting. It is suggested that the development of a nonuniform strain is required for rupture failure of the membranes.

Examination of one case in which a membrane bonded to a solid substrate in which a crack or joint opens suggests that the mode of failure may be either shear failure of the bituminous adhesive or rupture failure of the membrane. The limiting parameter appears to be the thickness of the adhesive used; values of adhesive thickness above a critical value for a particular adhesive result in membrane rupture and below this value the mode of failure is shear failure of the adhesive. The value of this critical thickness at any particular temperature is influenced by the shear properties of the adhesive and the tensile properties of the membrane.

These conclusions must be regarded as tentative at this stage. They suggest the need for further work on the properties of membranes as they exist in service. Attention must be directed also to the properties of substrates, particularly as these may lead to nonuniform high strains in membranes in practice. Finally, it is believed that further useful evidence may be obtained from the field examination of failures if the possibilities suggested in this paper are kept in mind.

Acknowledgments

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