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8632

A NEW APPROACH TO ROOF SYSTEM DESIGN

by

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U. S. DEPARTMENT OF COMMERCE
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ABSTRACT

Failures of bituminous built-up roofing membranes in service which result from thermally and mechanically induced stresses are related to some physical properties of the membrane such as breaking strength, elastic modulus, and coefficient of linear thermal expansion. A technique for preparing extremely uniform built-up roofing membrane test specimens is described. The results of load-strain tests and linear thermal expansion measurements for three bituminous built-up membranes are given at temperatures of 30°F (-1.1°C), 0°F (-17.8°C), and -30°F (-34.4°C). A Thermal Susceptibility Factor based on these properties is proposed and values are given for the three membranes. The Thermal Susceptibility Factor is related to performance in service. The utilization of the factor as a guide to manufacturers, architect-engineers, and roofing contractors in the manufacture, selection, and application of components and in the design of a roofing system is proposed.

1. INTRODUCTION

In 1964, the amount of built-up roofing components produced was sufficient to cover over 1.7 billion square feet (17 million squares) of roof area at a cost in excess of 450 million dollars. A large number of roofing systems constructed from these components will perform adequately for 20 or more years. However, the small percentage which are destined to fail prematurely will present serious and costly problems to manufacturers who produce the components of the system, the architects who design the systems, the contractors who apply them, and the building owners and occupants who expect good service from them.

In the design and construction of a roofing system, the architect and roofing contractor have little flexibility. They must rely either on their past experience with the performance of a specific system under known exposure conditions or on the material and application specifications recommended by manufacturers. In order to impart some flexibility to those charged with responsibilities involving the design and construction of a

roofing system, there is a need for criteria by which one can select the suitable materials and proper design for a roofing system which will perform adequately under specific exposure conditions.

The performance of a roofing system cannot be evaluated entirely on the basis of the properties of the individual components. An understanding of the interdependence and interaction between and among components is of paramount importance and must be considered. This is apparent from the discussion, by various authors, of problems such as blistering, wrinkle cracking and membrane shrinkage failures [1, 2, 3, 4, 5, 6]*, frequently associated with bituminous built-up roofing systems. Nevertheless, this does not preclude that the properties of the individual components can be ignored. Indeed, it is most important that in order to comprehend the performance of the total system the function of each individual component must also be understood. It was with this view in mind that this research was conducted.

The object of this research was to obtain data on some engineering properties of conventional built-up membranes and to relate these data to the performance of roofing systems in service. Another object was to propose the utilization of these data as a guide to the manufacturer, the architect-engineer, and the roofing applicator in the manufacture, selection, and application of components as well as in the design of a roofing system.

2. THERMALLY AND MECHANICALLY INDUCED STRESSES

Any discontinuity in the waterproofing element of the roofing system generally leads to a failure of the total system from both a thermal and weatherproofing standpoint. Recent experience has shown that splitting of built-up roofing membranes is a frequent cause of this discontinuity [7]. Initially it was believed that roofing splits resulted from shrinkage of the membrane due to thermally induced stress alone. However, recent studies by Jones [8] and Cullen [9] on engineering properties of bituminous built-up membranes have indicated that this is not the case and mechanically induced stresses must also be considered.

Mechanical stresses induced in the roofing membrane by differential movements between units of the substrate as evidenced by cracks or joints have been discussed by Koike [10]. He derived equations describing the conditions of rupture for a bituminous membrane in relation to some

*Figures in brackets indicate literature references at the end of this report.

physical properties of the membrane and the adhesive system used to bond the membrane to the substrate. Further, he confirmed the validity of the equations by laboratory experiments. For example, when the shear strength (τ_a) of the adhesive between the substrate and the membrane is equal to or exceeds a quantity expressed as follows:

$$\tau_a \geqq S \sqrt{\frac{G}{(E)\ (t_a)\ (t_m)}} \qquad \text{where} \qquad (1)$$

S = Tensile strength of bituminous membrane, lb/in.
G = Modulus of elasticity of adhesive in shear, lb/in.^{2}
E = Modulus of elasticity of membrane, lb/in.^{2}
t_a = Thickness of adhesive, in.
t_m = Thickness of membrane, in.

the membrane will fail when the width (W) of the separation in the substrate is equal to or exceeds a quantity expressed as follows:

$$W \geqq 2S \sqrt{\frac{t_a}{(E)\ (G)\ (t_m)}} \qquad (2)$$

On the other hand, when the shearing strength (τ_a) of the adhesive is less than the value of equation (1), a shear failure will occur within the adhesive and regardless of the width of the separation in the substrate, no rupture will occur in the membrane.

In connection with thermally induced stresses in bituminous built-up membranes, Cullen [6] proposed a Thermal Susceptibility Factor wich will prove useful to predict the ability of a membrane to tolerate movements produced by rather sudden temperature changes. Again this factor is related to some engineering properties of the built-up membrane and can be expressed as follows:

$$TSF = \frac{S}{E\,\alpha} \qquad \text{where} \qquad (3)$$

TSF = Thermal Susceptibility Factor
E = Modulus of Elasticity, lb/in.*
S = Breaking Load, lb/in.*
α = Coefficient of linear thermal expansion per °F.

*The breaking loads and moduli of elasticity are expressed in lb/in. rather than the more conventional dimensions of lb/in.^{2} since a previous study [8] has indicated the effects of the bonding bitumen on the strength characteristics of a bituminous built-up membrane are negligible.

Assuming the relations proposed by Koike and Cullen are valid, it is evident that the resistance of a roofing system to mechanically and thermally induced stresses can be predicted, in a qualitative manner at least, by measuring some physical properties of the composite membrane and the adhesive system used to attach the membrane to the substrate. These measurements should be made, of course, at temperatures corresponding to the minimum temperatures expected at the exposure location. Further, when a correlation between these factors and performance in service is established, it will be possible to assign numerical values to these factors to predict acceptable performance of a specific roofing system under specific climatic exposures. These values could be utilized by the manufacturer, architect-engineer, and roofing contractor in the manufacture of components and in the design and application of roofing systems.

3. MATERIALS AND SPECIMEN PREPARATION

Three types of bituminous saturated or impregnated felts and two types of bitumen which are currently being used in the construction of built-up roofs were selected for the study.

For the first series of tests, each specimen consisted of four plies of the saturated felt adhered to each other without the use of additional bitumen or mechanical fasteners. For the second series of tests, each specimen consisted of four plies of the saturated felt adhered to each other with the appropriate bitumen applied at a spreading rate of about 25 lb. per 100 sq. ft., which is comparable to standard roofing practice. The samples are identified as Samples A, B, or C, depending on their composition.

The four-ply specimens of felt alone were prepared by heating 4-in. X 8-in. sections of felt to about 248°F (120°C) for about 5 minutes and while hot, four plies were pressed together in a laboratory press in such a manner as to utilize the bituminous saturant as an adhesive.

The four-ply composite membrane specimens were prepared by heating the bituminous cement to 212 to 266°F (100-130°C). The heated bitumen was poured on an 8- X 4-inch section of the saturated felt placed on a larger piece of unlacquered cellophane and a second section of felt was placed on the bitumen to form a sandwich. This in turn was covered with unlacquered cellophane and placed in an unheated laboratory press using two 0.125-inch diameter rods, placed on either side and adjacent to the specimen, as spacers. Sufficient pressure was applied so that the platens of the press were separated from each other by the spacers. When cool, the two-ply sandwich was taken from the press, the top piece

of cellophane removed and two additional plies were applied (one at a time) by repeating the above process using spacers having diameters of 0.218 inch and 0.312 inch for the third and fourth plies, respectively.

The specimens were chilled to about 32°F (0°C) and dumbbell specimens were stamped out using a suitable die in the laboratory press. Figure 1 shows the die, the test specimen, and a cross section of the test specimen.

It is extremely important that felts in any single specimen be oriented and identified in respect to longitudinal (machine) and transverse (across machine) directions.

4. LOAD-STRAIN PROPERTIES IN TENSION

The load-strain properties of the saturated felts and the composite membranes were measured on triplicate specimens employing a tensile testing machine equipped with a temperature chamber to control the specimen temperature within ±5°F (±2.7°C) during the test. The load-strain measurements were made at -30°F (-34.4°C), 0°F (-17.8°C), and +30°F (-1.1°C). The temperature was measured by inserting a copper-constantan thermocouple in a typical specimen. This was believed to be a realistic temperature range for roofs exposed in many areas of the United States where failures have occurred. The gage length as defined by the distance between the jaws of the testing machine was 4.5 inches and a straining rate of 0.05 inches per minute (1.1% per minute) was used in each determination.

The averaged results of the load-strain measurements for triplicate 4-ply specimens of felts and membranes (identified as Samples A, B, & C) are reported to the nearest 10 lbs. in Tables 1, 2, and 3.

5. LINEAR THERMAL MOVEMENT

Linear thermal movement measurements were made on specimens prepared as described in Section 3 using a 5-inch gage length in accordance with the procedure described elsewhere [9]. The coefficients of linear thermal expansion over a temperature range of +30°F to -30°F (-1.1°C to -34.4°C) are reported in Table 4.

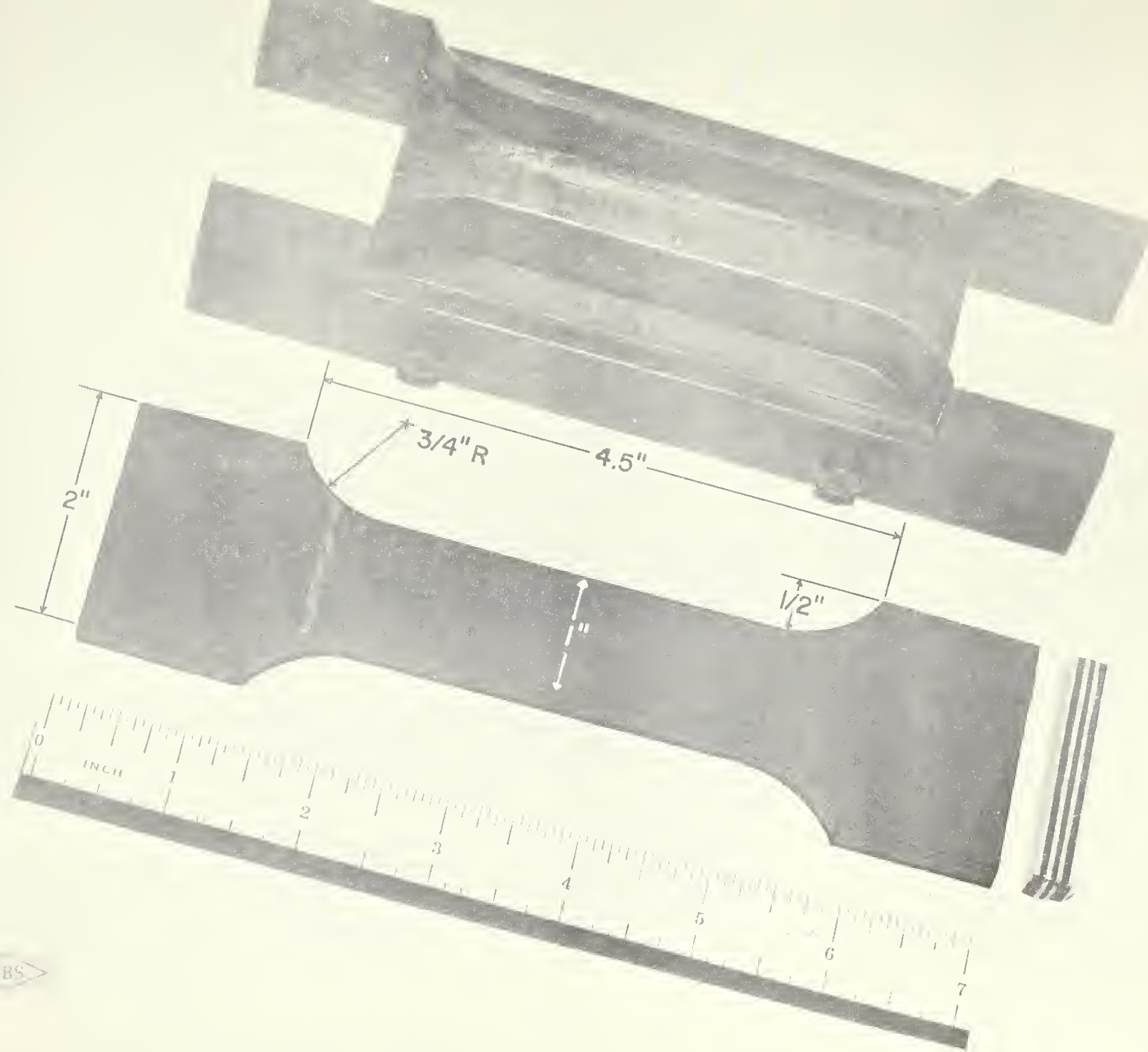
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TABLE 1. LOAD-STRAIN PROPERTIES - SAMPLE A

Specimen	Temp. °F.	Direction *	Breaking Load lb/in.	Breaking Strain %	Elastic Modulus lb/in
4-Ply saturated felt only	-30	L	380	1.1	9.2×10^4
		T	270	1.3	6.1×10^4
	0	L	400	2.2	7.3×10^4
		T	280	3.1	4.9×10^4
	+30	L	270	2.0	5.8×10^4
		T	150	3.1	2.7×10^4
4-Ply composite Membrane	-30	L	480	1.7	4.3×10^4
		T	310	1.4	3.0×10^4
	0	L	400	2.6	2.8×10^4
		T	300	3.2	1.9×10^4
	+30	L	270	2.3	2.1×10^4
		T	180	4.0	1.3×10^4

* L - Longitudinal

T - Transverse

TABLE 2. LOAD-STRAIN PROPERTIES - SAMPLE B

Specimen	Temp. °F.	Direction *	Breaking Load lb/in.	Breaking Strain %	Elastic Modulus lb/in
4-Ply saturated felt only	-30	L	170	1.2	1.8×10^4
		T	130	1.3	1.3×10^4
	0	L	180	1.5	1.4×10^4
		T	160	1.6	1.5×10^4
	+30	L	150	1.7	1.2×10^4
		T	120	1.6	1.0×10^4
4-Ply composite Membrane	-30	L	230	1.4	2.0×10^4
		T	170	1.4	1.7×10^4
	0	L	200	1.4	1.7×10^4
		T	200	1.7	1.5×10^4
	+30	L	180	2.6	1.3×10^4
		T	150	2.3	1.1×10^4

* L - Longitudinal

T - Transverse

TABLE 3. LOAD-STRAIN PROPERTIES - SAMPLE C

Specimen	Temp. °F.	Direction *	Breaking Load lb/in.	Breaking Strain %	Elastic Modulus lb/in
4-Ply saturated felt only	-30	L	390	1.6	3.7×10^4
		T	180	1.1	2.6×10^4
	0	L	350	2.1	2.7×10^4
		T	180	2.6	1.4×10^4
	+30	L	170	2.8	1.4×10^4
		T	60	4.7	0.4×10^4
4-Ply composite Membrane	-30	L	380	1.3	4.0×10^4
		T	210	1.2	2.6×10^4
	0	L	400	2.2	4.9×10^4
		T	180	2.8	2.9×10^4
	+30	L	240	2.5	3.0×10^4
		T	120	3.0	1.2×10^4

* L - Longitudinal

T - Transverse

TABLE 4. APPARENT LINEAR THERMAL EXPANSION COEFFICIENT OF 4-PLY BUILT-UP MEMBRANES (TEMP. RANGE +30°F to -30°F)

	Expansion Coefficient $(°F)^{-1}$ Longitudinal Dir.	Transverse Dir.
Sample A - 4-ply composite membrane	7.8×10^{-6}	16.9×10^{-6}
Sample B - 4-ply composite membrane	11.7×10^{-6}	14.6×10^{-6}
Sample C - 4-ply composite membrane	19.4×10^{-6}	39.6×10^{-6}

6. THERMAL SUSCEPTIBILITY FACTOR

In order to establish a numerical value for thermal shock resistance, a Thermal Susceptibility Factor was calculated for each of the composite membranes included in the program. The values were obtained for temperatures of -30°F (-34.4°C), 0°F (-17.8°C), and 30°F (-1.1°C) by substituting the data in equation 3 (see section 2). The factors rounded off to the nearest fifty for the respective built-up membranes in both the longitudinal and transverse directions of the reinforcing felts are reported in Table 5.

7. RELATION BETWEEN SPLITTING FAILURES AND THE THERMAL SUSCEPTIBILITY FACTORS.

Investigations by Cullen [9] and Moseley [7] of splitting failures in bituminous built-up membranes during recent years on roofs protecting structures in the colder climates have revealed some factors which frequently contribute to such failures. The factors include, among others, climate, orientation of the felt in the membrane and the thermal characteristics of the substrate.

It is interesting to develop a relation between the frequency of splitting failures of membranes exposed to actual weathering conditions and the magnitude of the Thermal Susceptibility Factors reported in Table 5.

7.1 Climate

The incidence of splitting failures was greater in the colder climates and the failures were frequently reported following periods of extremely cold weather with little or no snow cover. It can be seen from Table 5 that with few exceptions the Thermal Susceptibility Factor decreases in value as the temperature is decreased. It appears that a correlation is established.

TABLE 5. THERMAL SUSCEPTIBILITY FACTORS FOR 4-PLY COMPOSITE MEMBRANES

Sample	Temp. °F.	Direction of Felt in Membranes: Longitudinal	Transverse
A	-30	1450	600
	0	1850	950
	30	1650	800
B	-30	1000	700
	0	1050	900
	30	1200	950
C	-30	500	200
	0	400	250
	30	400	250

7.2 Thermal Characteristics of Substrate

Splitting failures due to membrane shrinkage were more common in bituminous built-up membranes applied to substrates having high thermal insulating values. Since membranes placed over such substrates are subcooled to a greater extent due to radiative cooling than similar membranes placed over more dense substrates [11], the conclusion can be made that the Thermal Susceptibility Factor will have a lower value due to the lower temperature. This is substantiated by the data reported herein.

7.3 Orientation of Reinforcing Felt

Splitting failures resulting in part from membrane shrinkage were observed more frequently in the transverse direction of the reinforcing felt than in the longitudinal direction, thus indicating the anisotropic behavior of the bituminous built-up membrane. It appears to be more than coincidental that the Thermal Susceptibility Factor also demonstrates this anisotropic behavior in that it is, in most cases, considerably lower in the transverse direction than in the longitudinal direction.

7.4 Composition of Built-Up Membrane

The significant differences in the values of the susceptibility factors among membranes identified as Samples A, B, and C would imply differences in performance among the membranes in field service regarding splitting failures. However, to our knowledge, a correlation has not been established to date since sufficient data on splitting failures in the field in respect to composition of the membrane have not been developed.

8. APPLICATION OF THEMAL SUSCEPTIBILITY FACTOR

The differences in the values among the Thermal Susceptibility Factors of the various membranes in relation to composition, temperature and felt orientation are apparent and are indicative of the thermal shock resistance of the respective membranes in service. The higher value indicates the better thermal shock resistance. The question now arises as to the application of this factor to roofing system performance in the field.

We believe that a knowledge of the factor will prove useful in predicting the ability of a built-up membrane to withstand stresses induced by thermal movement. Further, the value of the factor assigned to a roofing membrane will depend to a large extent on the climate to which exposed, the position of the membrane in the roofing system, the orientation of the felt in the membrane and to the area of the roofing unbroken by expansion joints. For example, a higher Thermal Susceptibility Factor will be required for a membrane exposed in an area experiencing an

average January temperature of 20°F than that required for another membrane to be exposed where the average January temperature is 30°F. Similarly, a higher factor will be necessary for a membrane placed over a substrate having a high thermal insulating value than that needed for a membrane placed directly on a concrete deck. We would also expect that a higher Thermal Susceptibility Factor would be desirable for membranes on roofs where large areas are involved as opposed to those having smaller areas.

In conclusion, we are reluctant to suggest, at this time, even a range of values for the Thermal Susceptibility Factor to describe an acceptable roof membrane under given conditions because adequate supporting information from field service is not available. However, we believe that the collection and utilization of these data by the manufacturer, the architect-engineer, the roofing contractor, and the ultimate consumer will prove immediately beneficial and in the future may provide him with the flexibility to manufacture, design and apply suitable roofing systems for any combination of circumstances.

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