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Thermal-Shock Resistance for Built-Up Membranes

William C. Cullen and Thomas H. Boone

Building Research Division
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

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Contents

Section 1

Progress in the Development of a Thermal-Shock Resistance Factor for Bituminous Built-up Roofing Membranes [1]

William C. Cullen and Thomas H. Boone

The resistance of bituminous built-up roofing membranes to thermally induced forces is considered in terms of their strength properties such as breaking load in tension, modulus of elongation and apparent linear thermal expansion coefficient. The development of a Thermal-Shock Resistance Factor is described and values are given for three bituminous built-up membranes at temperatures of −30 °F (−34.4 °C), 0 °F (−17.8 °C), 30 °F (−1.1 °C) and 73 °F (22.8 °C). The apparent relation between the values obtained in the laboratory and the observed performance of roofing membranes in service is considered. The utilization of the Thermal-Shock Resistance Factor in the reduction of potential failures of bituminous built-up roofing membranes in service from thermally induced forces is also discussed.

Key Words: Development, roofing membrane, strength properties, thermally induced forces, thermal-shock resistance factor.

Contents

1. Introduction

In 1964 the amount of built-up roofing components produced was sufficient to cover over 1.7 billion square feet of roof area at an installed cost in excess of 450 million dollars. A large number of roofing systems constructed from these components should 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 choice. 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 permit greater flexibility, there is a need for design criteria by which the architect-engineer and materials manufacturer can select suitable materials to assure a properly designed roofing system which will perform adequately under specific exposure conditions.

The performance of a roofing system cannot be predicted or 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 by the designer. This is apparent from the discussion, by various authors, of problems such as blistering, wrinkle cracking, and membrane shrinkage fail-

[1] Also published as part of ASTM STP 409, American Society for Testing and Materials (1966).

ures [1, 2, 3, 4, 5, 6, 7],[2] frequently associated with bituminous built-up roofing systems. Nevertheless, this does not mean 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.

The object of this research was to obtain laboratory data on some engineering properties of conventional bituminous built-up membranes and to attempt to relate these data to the performance desired of roofing systems operating under service conditions. A second objective was to develop a procedure for utilizing these data in such a manner that would be useful as a guide to the manufacturer, the architect-engineer, and the roofing contractor in the manufacture, selection, and application of components of a roofing system.

[2] Figures in brackets indicate literature references at the end of this paper.

2. Thermally and Mechanically Induced Forces

The authors' experience over many years with bituminous built-up roof performance in service has indicated that many failures can be attributed to factors other than mechanically and thermally induced forces with which this paper deals. Therefore, this paper should not be construed to imply that these other factors, such as moisture movement, wrinkle cracking, blistering, etc., are not important considerations in many bituminous built-up roof failures.

Any rupture in the waterproofing element of the roofing system generally leads to a failure of the total roofing system from both a heat transfer and weatherproofing viewpoint. Recent experience has shown that splitting of built-up roofing membranes is a frequent cause of failure [7].

Cullen [6] suggested that the rather sudden temperature changes which occur in roofing membranes are a key element in splitting failures. Thermal shock stresses therefore can be expected to be greater in roofing materials than in other components of a building construction. In this connection he proposed the development of a thermal-shock factor which should prove useful for predicting the ability of a roofing membrane to tolerate, without rupture, the movements produced by the rather sudden temperature changes. The thermal-shock resistance factor which was proposed depends upon some laboratory determined properties of the built-up membrane as given in eq (1).

$$\mathrm{TSF}=\frac{S}{M\alpha} \tag{1}$$

where:

TSF = Thermal-Shock Resistance Factor
S = Breaking load, lb/in (see footnote 3)
M = Modulus of Elongation (initial tangent), lb/in (see footnote 3).
α = Apparent Linear Thermal Expansion Coefficient, per °F.

If a restrained object is heated or cooled, thermal stresses are induced that are proportional to the coefficient of linear thermal expansion, the modulus of elasticity and the temperature change. This relation has been expressed by eq (2) [9].

$$f_t = E\epsilon\,\Delta t \tag{2}$$

where:

f_t = Stress due to temperature change, psi
E = Modulus of elasticity, psi
ϵ = Coefficient of linear expansion, per ° F
Δt = Change in temperature ° F.

If we rewrite eq (2) as follows:

$$\Delta t=\frac{f_t}{E\epsilon}, \tag{3}$$

it becomes apparent that the proposed Thermal-Shock Resistant Factor takes on a physical significance. Numerically it is equivalent to the the temperature drop required to produce a stress equal to the ultimate. This assumes constant properties and perfect elasticity which of course is not the case here.

The higher the value for the Thermal-Shock Resistance Factor for a roofing membrane the more resistant it should be to splitting failures. Therefore, the more resistant built-up membranes will have a high breaking load, a low modulus of elongation, and a low coefficient of apparent linear thermal expansion.

At this time the proposed test should be recognized as an empirical one which may or may not correlate with the performance of a specific built-up roofing membrane in service. Therefore a high value for the factor does not necessarily infer that in all cases the membrane will exhibit better performance characteristics than one displaying a lower value.

Initially, it was believed that roofing splits resulted solely from shrinkage of the membrane due to forces induced by sudden temperature changes. However, recent studies by Jones [8] and Cullen [10] on engineering properties of bituminous built-up membranes have indicated that mechanically induced forces must also be considered.

Mechanical stresses are sometimes induced in the roofing membrane by cracks which occur in the substrate or by differential movements between units of the substrate. Koike [11] discusses this problem. He derived eqs (4) and (5) below that

[3] The breaking loads and moduli of elongations are expressed in pounds per inch width of membrane since a previous study [8] has shown that the overall thickness of the membrane is negligible. The elongation moduli are the slopes of the initial tangent to the load-strain curves.

describe the conditions for rupture of a bituminous membrane in relation to some physical properties of the membrane and the adhesive system used to bond the membrane to the substrate. He states that a roofing membrane will rupture if the increase in width (ΔW) of a crack in the substrate is equal to or exceeds the quantity expressed on the right side of eq (4), provided that the shear strength (τ_a) of the adhesive between the membrane and the substrate is equal to or exceeds the quantity expressed by the right-hand side of eq (5).

On the other hand, when the shearing strength (τ_a) of the adhesive is less than the value on the right side of eq (5), a shear failure will occur within the adhesive and, regardless of the width of the crack produced by movement in the substrate, no rupture will occur in the membrane.

$$\Delta W \gtreqless 2S\sqrt{\frac{t_a}{(E)(G)(t_m)}} \qquad (4)$$

$$\tau_a \gtreqless S\sqrt{\frac{(G)}{(E)(t_a)(t_m)}} \qquad (5)$$

where:

ΔW=Increase in width of crack in the substrate, cm

S=Breaking load in tension, kg/cm

E=Modulus of elasticity (initial tangent) of membrane in tension, kg/cm^2

t_a=Thickness of adhesive between membrane and substrate, cm

G=Modulus of elasticity (secant modulus) of binding bitumen in shear, kg/cm^2

t_m=Thickness of membrane, cm

τ_a=Shearing strength of adhesive bitumen, kg/cm^2

Although Koike demonstrated the validity of the equations by laboratory experiments involving one layer of an asphalt saturated and coated felt bonded to a concrete panel with a blown petroleum asphalt, he concluded that the equations were not intended to predict the performance of a roofing in service but that they may prove helpful in the development of improved roof coverings.

It should be noted here that, to our knowledge, data are not available on these properties for either single or multiple ply membrane currently in use in the United States. Therefore, the use of the equations as a guide for the performance of built-up roof coverings in service is not presently feasible.

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. Table 1 identifies the materials.

TABLE 1. *Materials used in the preparation of specimens*

Materials	ASTM Specification
Bitumens:	
Asphalt	D312, Mineral Sur. Flat.
Coal-tar-pitch	D450, Type A.
Reinforcing felt:	
Asphalt saturated organic felt	D226, 15 lb type.
Asphalt impregnated glass felt	([a]).
Coal-tar saturated organic felt	D227.

[a] "Perma Ply No. 11," as manufactured by the Owens-Corning Fiberglas Corporation. The commercial material is identified in this paper in order to specify the experimental procedure adequately. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards nor does it imply that the material identified is necessarily the best available for the purpose.

Each specimen consisted of four plies of the felt adhered to each other with the selected bitumen applied at a spreading rate of about 25 lb per 100 sq ft, which is comparable to normal roofing practice.

The four-ply built-up specimens were prepared by heating the bituminous cement to 212 to 266 °F (100 to 130 °C). The heated bitumen was poured on an 8- × 4-in 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. Sufficient pressure was applied so that the platens of the press were separated from each other by two 0.125-in diam spacers, placed on either side and adjacent to the specimen. 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 in and 0.312 in for the third and fourth plies, respectively.

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

The felts in any single specimen were oriented and identified in respect to longitudinal (with machine) and transverse (across machine) directions since they exhibit anisotropic behavior.

4. Load-Strain Properties in Tension

The load-strain properties of three specimens in each direction were measured at −30 °F (−34.4 °C), 0 °F (−17.8 °C). 30 °F (−1.1 °C), and 73 °F (22.8 °C) employing a tensile testing machine equipped with temperature chamber to control the specimen temperature within ±5 °F

(±2.7 °C) during the test. The temperatures selected were believed to cover 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 in and a straining rate of 0.05 in per minute (1.1% per minute) was used in each determination. We recognized that this rate of loading which was at the slowest rate permitted by the testing apparatus, was significantly higher than that likely to be experienced at subfreezing temperatures in service. In our opinion the rate of loading will influence both the values obtained for the Thermal-Shock Resistant Factors and the performance of built-up roofing membranes in service.

The averaged results of the load-strain measurements are reported to the nearest 10 lb in tables 2, 3, 4, and 5. The values for the elongation moduli are the slopes of the initial tangent to the load-strain curves. The standard deviation among replicates for breaking loads is 20 lb/in; thus the standard error for the values in the tables is $\frac{20}{\sqrt{3}} \cong 12$ lb/in; or an uncertainty of ±25 lb/in. For elongation modulus, the standard deviation among replicates is a function of the temperature and has the following values:

Temperature (°F)	−30	0	30	73
Standard deviation (lb/in)	1200	1600	2100	2300

Table 2. *Properties of bituminous built-up membranes at −30 °F*

Membrane	Direction[a]	Breaking load (S)[b]	Elongation modulus (M)[b]	Apparent linear thermal exp. coefficient (α)[c]	Thermal-shock factor
		lb/in	*lb/in*	$(°F)^{-1}$	
Asphalt, asphalt-sat. organic felt	L	480	4.3×10^4	11×10^{-6}	1000
	T	310	3.0×10^4	21×10^{-6}	500
Coal-tar-pitch, coal-tar-sat. organic felt	L	380	4.0×10^4	19×10^{-6}	500
	T	210	2.6×10^4	29×10^{-6}	300
Asphalt, asphalt-sat. glass felt	L	230	2.0×10^4	18×10^{-6}	650
	T	170	1.7×10^4	26×10^{-6}	400

[a] L—Longitudinal (with machine).
T—Transverse (across machine).
[b] Average of three specimens.
[c] Temperature Range +30 to −30 °F.
Source: NBS Mono. No. 89 (1965).

Table 3. *Properties of bituminous built-up membranes at 0 °F*

Membrane	Direction[a]	Breaking load (S)[b]	Elongation modulus (M)[b]	Apparent linear thermal exp. coefficient (α)[c]	Thermal-shock factor
		lb/in	*lb/in*	$(°F)^{-1}$	
Asphalt, asphalt-sat. organic felt	L	400	2.8×10^4	11×10^{-6}	1300
	T	300	1.9×10^4	21×10^{-6}	750
Coal-tar-pitch, coal-tar-sat. organic felt	L	400	4.9×10^4	[illegible]$\times10^{-6}$	450
	T	180	2.9×10^4	29×10^{-6}	200
Asphalt, asphalt-sat. glass felt	L	200	1.7×10^4	18×10^{-6}	650
	T	200	1.5×10^4	26×10^{-6}	500

[a] L—Longitudinal (with machine).
T—Transverse (across machine).
[b] Average of three specimens.
[c] Temperature Range +30 to −30 °F.
Source: NBS Mono. No. 89 (1965).

Table 4. *Properties of bituminous built-up membranes at 30 °F*

Membrane	Direction[a]	Breaking load (S)[b]	Elongation modulus (M)[b]	Apparent linear thermal exp. coefficient (α)[c]	Thermal-shock factor
		lb/in	*lb/in*	$(°F)^{-1}$	
Asphalt, asphalt-sat. organic felt	L	270	2.1×10^4	11×10^{-6}	1200
	T	180	1.3×10^4	21×10^{-6}	700
Coal-tar-pitch, coal-tar-sat. organic felt	L	260	3.0×10^4	19×10^{-6}	500
	T	120	1.2×10^4	29×10^{-6}	350
Asphalt, asphalt-sat. glass felt	L	180	1.3×10^4	18×10^{-6}	800
	T	150	1.1×10^4	26×10^{-6}	500

[a] L—Longitudinal (with machine).
T—Transverse (across machine).
[b] Average of three specimens.
[c] Temperature Range +30 to −30 °F.
Source: NBS Mono. No. 89 (1965).

Table 5. *Properties of bituminous built-up membranes at 73 °F*

Membrane	Direction [a]	Breaking load (S) [b]	Elongation modulus (M) [b]	Apparent linear thermal exp. coefficient (α) [c]	Thermal-shock factor
		lb/in	*lb/in*	$(°F)^{-1}$	
Asphalt, asphalt-sat. organic felt	L	190	1.9×10^4	3.2×10^{-6}	3000
	T	130	9.4×10^3	5.3×10^{-6}	2600
Coal-tar-pitch, coal-tar-sat. organic felt	L	160	1.3×10^4	2.0×10^{-6}	6150
	T	90	5.2×10^3	3.2×10^{-6}	5400
Asphalt, asphalt-sat. glass felt	L	180	1.4×10^4	2.5×10^{-6}	5150
	T	170	1.2×10^4	2.5×10^{-6}	5650

[a] L—Longitudinal (with machine).
T—Transverse (across machine).
[b] Average of three specimens.
[c] Temperature Range 100 to −60 °F.
Source: NBS Tech. Note 231 (Dec. 1963).

5. Apparent Linear Thermal Expansion Coefficients

The apparent linear thermal expansion coefficient for four-ply built-up membranes over a temperature range of +30 to −30 °F (−1.1 to −34.4 °C) were taken from reference [10] and are given in tables 2, 3, and 4. Coefficients for similar membranes over a temperature range of 100 °F (37.8 °C) to 60 °F (15.6 °C) were calculated from the curves given in reference [6] and are given in table 5.

6. Thermal-Shock Resistance Factor

In order to establish a numerical scale for thermal shock resistance, a Thermal-Shock Resistance Factor was calculated for each of the composite membranes included in the program. The values were obtained by substituting the data in eq (1) (see sec. 2). The factors were rounded off to the nearest 50 and are given in tables 2, 3, 4, and 5.

7. Relation Between Splitting Failures and the Thermal-Shock Resistance Factors

Investigations by Cullen [10] of splitting failures in bituminous built-up membranes during recent years on roofs exposed to low and changing temperatures have revealed some factors which frequently contribute to such failures. These include, among others, climate, orientation of the felt in the membrane and the thermal characteristics of the substrate.

It is interesting to speculate on a relationship between the frequency of splitting failures of membranes exposed to actual weathering conditions and the value of the Thermal-Shock Resistance Factors reported herein.

7.1. Climate

The observed incidence of splitting failures which were attributed in part to thermal shrinkages was greater in the colder climates and failures were frequently reported following periods of extremely cold weather with little or no snow cover. The results of this study show that with few exceptions the Thermal-Shock Resistance Factor is lower in value at low temperature.

7.2. Thermal Characteristics of Substrate

Splitting failures were observed more frequently in bituminous built-up membranes applied to substrates having high thermal insulating values than in those placed directly on more dense substrates.

Built-up roof membranes placed on insulation are subjected to both higher temperatures when exposed to solar heating and to lower temperatures during the nighttime due to radiative cooling than are their non-insulated counterparts [12]. Therefore, the lower temperatures experienced by a membrane placed over insulation will result in a lower value for the Thermal-Shock Resistance Factor than for a similar membrane placed over another substrate. The lower values for the Thermal-Shock Resistance Factor in the Laboratory were obtained at the lower temperatures indicating consistency with field observations.

7.3. Orientation of Reinforcing Felt

Splitting failures in built-up membranes resulting in part from thermal shrinkage were observed almost exclusively perpendicular to the transverse direction of the reinforcing felt. This indicated the anisotropic behavior of the bituminous built-up membrane. The Thermal-Shock Resistance Factor data given in the tables also show this anisotropic behavior probably because the strength is appreciably lower and the apparent linear thermal expansion coefficient is considerably higher in the transverse direction as compared to the longitudinal direction.

7.4. Composition of Built-Up Membrane

The significant differences in the values of the Thermal-Shock Resistance Factors among the membranes would imply differences in perform-

259-508 O-67—2

ance among these membranes under service conditions regarding splitting failures. However, to our knowledge, this has not been established. In fact, splitting failures under service conditions have been observed and reported for each type of bituminous built-up membrane included in this investigation. Further, there are factors other than thermal movement, such as moisture or structural movements, which are known to contribute to a lesser or greater extent in the observed failures and they must also be considered. There is a need for further investigation in this area as stated in section 2.

8. Conclusions

We recognize the preliminary nature of both the test methods and the test results used to determine the values of the Thermal-Shock Resistance Factors reported herein. Nevertheless we believe that a knowledge of this factor prior to installation will prove useful in predicting the ability of a built-up membrane to withstand forces induced by thermal shock. Further, the value of the factor assigned to a roofing membrane will depend to a large extent on the climate to which exposed, whether the membrane is placed over insulation or not, the longitudinal or transverse orientation of the felt in the membrane and to the area of the roofing unbroken by expansion joints. For example, a higher Thermal-Shock Resistance 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-Shock Resistance Factor would be desirable for membranes on roofs where large areas are involved as opposed to those divided into smaller areas by expansion joints.

It is interesting to note that the data reported by Koike [11] and that reported herein support the validity of some suggestions made by Cullen [10] regarding the alteration of some conventional application techniques to reduce the incidence of splitting failures resulting from mechanically and thermally induced forces, as:

(a) The placement of the insulation boards with their long dimension parallel to the short dimension of the roof.

(b) The orientation of the roofing felt parallel to the long dimension of the roof.

(c) The use of an adhesive of optimum strength to secure the membrane to the substrate.

The authors acknowledge with thanks the assistance of W. H. Appleton and A. J. Turner in the preparation of the specimens and in making the measurements reported in this paper. The authors also acknowledge the advice and encouragement given to them by W. W. Walton and the members of the Tri-Service Committee.

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9. References

[1] C. E. Lund and R. M. Granum, Univ. of Minnesota Eng. Exp. Stn. Bulletin No. 34 (May 1952).

[2] W. B. Warden, Building Research Institute Monograph No. 1 (1960).

[3] D. E. Brotherson, Research Report 61–2, Small Homes Council-Building Research Council, University of Illinois (1961).

[4] G. O. Handegord, Technical Paper No. 182 of the Division of Building Research, National Research Council, Canada (June 1964).

[5] F. A. Joy, Better Building Report No. 5, College of Engineering, The Pennsylvania State University (Sept. 1963).

[6] W. C. Cullen, NBS Technical Note No. 231 (Dec. 1963).

[7] G. N. Moseley, An Explanation of Built-Up Roofing Tension Splits, Building Research Institute 1964 Fall Conference (November 1964).

[8] P. M. Jones, Recent Research on Bituminous Materials, ASTM STP–347 (1963).

[9] Perry, Robert H. and John H., (ed) Engineering Manual (1959).

[10] W. C. Cullen, NBS Mono. No. 89 (1965).

[11] Michio Koike, BRI Occasional Report No. 15, Building Research Institute, Japan (Dec. 1963).

[12] W. C. Cullen, W. H. Appleton, The Construction Specifier **16**, 5, 35 (October 1963).

FIGURE 1. *Cutting die, four-ply built-up roofing specimen and cross section of membrane.*

Section 2

Thermal-Shock Resistance for Bituminous Built-up Roofing Membranes—Its Relation to Service Life

William C. Cullen and Thomas H. Boone

The assignment of a service life to a bituminous built-up roofing system is frequently difficult because of the many variables involved. A knowledge of these variables, and of their effect on the performance of the total building system, will greatly assist in the selection of a roofing assembly and the assignment of a service life to such an assembly.

Some of the factors such as breaking load in tension, modulus of elongation, and apparent linear thermal expansion coefficient of roofing membranes of different composition are given for both laboratory-prepared and field-obtained samples. Membranes of 2, 3, and 4-plies of felt are included. The relations of some engineering properties of a roofing membrane to performance in service as expressed by a Thermal-Shock Resistance Factor are also given. Ways and means to reduce potential failures of bituminous built-up roofing membranes resulting from thermally induced forces are discussed.

Key Words: Bituminous-built-up roofing, roofing membrane, service life, thermal-shock resistance factor, tension splitting.

Contents

1. Introduction

Any rupture of the waterproofing element of a roofing assembly generally leads to failure of the total assembly, from both a weatherproofing and a heat transfer viewpoint. Moseley [1] [1] has indicated that tension splits which occur in the built-up membrane are frequent causes of failure. Cullen [2] suggested that the thermal movement which occurs in a bituminous built-up roofing membrane due to rapid temperature changes is often a contributing factor in tension splits. He proposed the utilization of a Thermal-Shock Resistance Factor to predict the ability of a built-up membrane to tolerate, without rupture, the forces induced by such temperature changes [3].

A roofing membrane will rupture when the thermal contraction equals or exceeds the ultimate elongation of the membrane. Since the force-extension curve is approximately linear below 30 °F (−1.1 °C), the ratio of tensile strength (S) to modulus of elongation (M) may be used to estimate the ultimate elongation. Thermal contraction is proportional to the coefficient of linear thermal expansion (α). Hence the merit of a membrane may be expressed by a Thermal-Shock Resistance Factor (TSRF) given by the following eq (1)

$$TSRF_1 = \frac{S}{M\alpha} \qquad (1)$$

[1] Figures in brackets indicate the literature references at the end of this paper.

where

$TSRF_1$ = Thermal-Shock Resistance Factor
S = Breaking load, lb/in (see footnote 2)
M = Modulus of elongation (initial tangent), lb/in (footnote 2)
α = Linear thermal expansion, per °F.

From this equation, it is seen that the higher the breaking load, the lower the coefficient of linear thermal expansion, and the lower the modulus of elongation, the more resistant to rupture is the membrane under thermal changes.

Cullen and Boone reported values for *TSRF* of three convential membranes at temperatures of −30 °F (−34.4 °C), 0 °F (−17.8 °C), 30 °F (−1.1 °C), and 73 °F (22.8 °C) in section 1 of this publication.

This paper presents values for Thermal-Shock Resistance Factors at 0 °F (−17.8 °C) for four built-up membranes constructed in the laboratory, consisting of 2, 3, and 4 plies of felt, respectively. In addition values for samples of bituminous built-up roofs with up to 25 years exposure in service are also given. In some cases the roof membranes from which the samples were obtained had tension splits which were attributed in part to thermally induced forces as illustrated by the sample shown in figure 1. In others no evidence of this type of failure was observed.

[2] The breaking loads and moduli of elongation are expressed in pounds per inch width of membrane since a previous study [4] had shown that the effect of the asphalt-cement on the strength characterisitcs of the membrane are negligible. The elongation moduli are the slopes of the initial tangent to the load-strain curves.

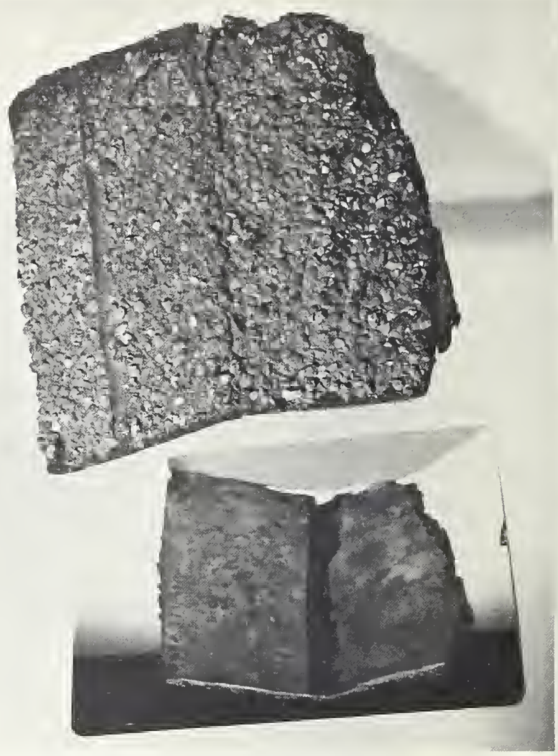

FIGURE 1. *Roof sample taken from field.* Note membrane split.

2. Experimental Details

2.1 Materials and Specimen Preparation

a. Laboratory

Four types of bituminous saturated or impregnated felts and two types of bitumen were selected for the preparation of laboratory specimens. Table 1 identifies the materials.

TABLE 1. *Materials used in the preparation of laboratory specimens*

Materials	ASTM specification
Bitumens:	
Asphalt	D312, Mineral Sur. Flat.
Coal-tar-pitch	D450, Type A.
Reinforcing felts:	
Asphalt saturated asbestos felt	D250, 15 lb type.
Asphalt saturated organic felt	D226, 15 lb type.
Asphalt impregnated glass felt	([a]).
Coal-tar saturated organic felt	D227.

[a] "Perma Ply No. 11," as manufactured by the Owens-Corning Fiberglas Corporation. The commercial material is identified in this paper in order to specify the experimental procedure adequately. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards nor does it imply that the material identified is necessarily the best available for the purpose.

The laboratory prepared specimens consisted of two, three, and four plies of felt adhered to each other with the appropriate bitumen applied at a spreading rate of about 25 to 30 lb per 100 sq ft, which is comparable to that obtained in good roofing practice. The laboratory samples were prepared, and dumbbell-shaped test specimens were cut by a procedure developed at the National Bureau of Standards as described in section 1 of this publication.

b. Field

In order to obtain samples from roofs of known history, it was necessary to rely upon the roofing industry. Samples were obtained through the cooperation of contractor associations, roofing manufacturers, and, in many cases, private roofing contractors.

Two samples, a minimum of one square foot in area, were cut from the selected roof. The samples were identified in respect to location, composition and felt orientation, and were forwarded to NBS. A history, as well as a diagram of the roof plan, frequently accompanied the samples. In some cases the roofs in question were observed by a NBS representative who selected the areas from which the samples were to be removed. In the cases where tension splits were apparent, samples were taken at or near the failure.

Information on the field samples relative to the location, age, composition, and number of plies is given in table 3.

The samples were prepared for test by removing the mineral surfacing (if present) and any adhering insulation. Dumbbell-shaped specimens similar to the laboratory-prepared test specimens were cut. Figure 2 shows a test specimen obtained from a roof membrane after 9 years exposure.

2.2. Load-Strain Properties in Tension

The load-strain properties and the breaking strength of the specimens were measured in duplicate (triplicate when sufficient specimens were available) 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 0 °F (−17.8 °C). The gage length, as defined by the distance between the jaws of the testing machine, was 4.5 in. A straining rate of 0.05 in per minute (1.1% per minute) was used in each determination.

We recognized that this rate of loading which was the slowest permitted by the testing apparatus, was significantly higher than that likely to be experienced in service. No doubt the rate of loading will influence both the values obtained for the Thermal-Shock Resistant Factors and more important the performance of a built-up roofing membrane in service.

2.3. Linear Thermal Expansion

The linear thermal expansion measurements were made on duplicate dumbbell-shaped specimens prepared as described in section 2.1, using a 5-in gage length in accordance with a procedure previously described by Cullen [2].

FIGURE 2. *A prepared test specimen of a membrane taken from the field after nine years exposure.*

3. Results

The average results of the load-strain measurements for the laboratory-prepared specimens are reported to the nearest 10 lb in table 2, and those of the samples obtained from roofs exposed under service conditions are reported in table 3. In each case the values for the elongation moduli are the slopes of the initial tangent to the load-strain curves.

The standard deviation among replicates for the breaking loads is 20 lb/in; thus the standard error for values in the tables is 12 lb/in; or an uncertainty of ±25 lbs/in. For the elongation modulus, the standard deviation among replicates is about 1600 lb/in at 0 °F.

The values of the apparent linear thermal expansion of the laboratory-prepared and field-obtained samples were calculated from data obtained over a temperature range of 30 to −30 °F (−1.1 to −34.4 °C), and are given in tables 2 and 3.

4. Discussion of Results

4.1. Effect of Number of Plies of Reinforcing Felt on the Strength Characteristics of a Built-up Membrane

As expected, figure 3 illustrates that the breaking load in tension for a multiple-ply built-up roofing specimen increased in proportion to the number of plies of felt in the membrane. Further, the composition of the bituminous-saturated roofing felt had a marked effect on the values of the breaking loads. Figure 4 shows the effect of the number of plies of reinforcing felt in the membrane, as well as the character of the felt, on the elongation modulus (initial tangent). Again a significant increase was noted in this property as the number of plies was increased.

Table 2 shows that, although the linear thermal expansion varied with the composition of the respective sample, the number of plies of felt in the membrane had no significant effect on the value of the coefficient of thermal expansion.

The value for the Thermal-Shock Resistance Factor was approximately the same for a 2-, 3-, or 4-ply membrane, despite the increase in breaking load with number of plies. The increased breaking load was offset by the increased elongation modulus, while the values of the coefficient of linear thermal expansion remained independent of the number of plies of felt.

If the Thermal-Shock Resistance Factor is a valid criterion, it may be concluded from the data

Table 2. *Properties of laboratory prepared built-up membranes at 0 °F*

Felt (bitumen)	No. Plies	Direction [a]	Break load (*S*)[b]	Elong. Mod. (*M*) [b]	Appar. lin. therm. exp coeff. (α) [c]	Thermal-shock factor
			lb/in	*lb/in*	$°F^{-1}$	
Organic (asphalt)	2	L	180	1.3×10^4	10×10^{-6}	1,350
		T	130	$.9\times10^4$	17×10^{-6}	850
	3	L	280	1.9×10^4	10×10^{-6}	1,500
		T	180	1.2×10^4	24×10^{-6}	650
	4	L	400	2.8×10^4	11×10^{-6}	1,300
		T	300	1.9×10^4	21×10^{-6}	750
Asbestos (asphalt)	2	L	170	2.0×10^4	10×10^{-6}	850
		T	80	0.9×10^4	26×10^{-6}	300
	3	L	270	2.8×10^4	8×10^{-6}	1,200
		T	120	1.3×10^4	30×10^{-6}	300
	4	L	310	3.3×10^4	11×10^{-6}	850
		T	130	1.6×10^4	32×10^{-6}	250
Glass (asphalt)	2	L	110	0.9×10^4	20×10^{-6}	620
		T	80	$.7\times10^4$	20×10^{-6}	600
	3	L	160	1.3×10^4	22×10^{-6}	540
		T	140	1.1×10^4	35×10^{-6}	360
	4	L	210	1.6×10^4	20×10^{-6}	660
		T	180	1.3×10^4	22×10^{-6}	610
Organic (coal tar)	2	L	200	2.5×10^4	22×10^{-6}	370
		T	100	1.7×10^4	33×10^{-6}	190
	3	L	330	3.9×10^4	25×10^{-6}	330
		T	150	3.3×10^4	42×10^{-6}	110
	4	L	450	4.8×10^4	27×10^{-6}	350
		T	220	3.9×10^4	42×10^{-6}	140

[a] L—Longitudinal (with machine).
T—Transverse (across machine).
[b] Average of three specimens.
[c] Temperature Range +30 to −30 ° F.

Table 3. *Properties of built-up roofing field samples at 0 °F*

Felt (bit.)	No. plies	Age yr	Source	Dir.[a]	Break load (*S*) [b]	Elong. mod. (*M*) [b]	Appar. lin. therm. exp. coeff. (α) [c]	Thermal-shock factor
					lb/in	*lb/in*	$°F^{-1}$	
Organic (asphalt)	3	6	Rockford, Ill.	L	240	4.5×10^4	16×10^{-6}	750
				T	140	4.7×10^4	41×10^{-6}	500
Organic (asphalt)	3	22	K. C., Mo.	L	220	2.3×10^4	15×10^{-6}	620
				T	130	1.6×10^4	30×10^{-6}	260
Organic (asphalt)	4	8	Waterloo, Iowa	L	230	1.4×10^4	25×10^{-6}	650
				T	80	1.1×10^4	23×10^{-6}	350
Glass (asphalt)	3	9	Omaha, Nebr.	L	90	1.8×10^4	20×10^{-6}	450
				T	80	1.2×10^4	19×10^{-6}	350
Organic (coal-tar)	3	12	Rockford, Ill.	L	210	3.8×10^4	20×10^{-6}	300
				T	70	2.0×10^4	31×10^{-6}	100
Organic (coal-tar)	4	20	Waterloo, Iowa	L	270	5.1×10^4	9×10^{-6}	550
				T	200	2.5×10^4	16×10^{-6}	500
Organic (coal-tar)	4	25	K. C., Mo.	L	490	5.1×10^4	13×10^{-6}	560
				T	260	4.9×10^4	23×10^{-6}	230

[a] L—Longitudinal (with machine).
T—Transverse (across machine).
[b] Average of three specimens.
[c] Temperature range +30 to −30 °F.

given herein that the resistance of a membrane to thermally induced forces is very nearly independent of the number of plies of reinforcing felt in the membrane.

The difference in the values of the linear thermal expansion property in respect to the orientation of the felt in a built-up membrane has previously been reported [2]. The values of the engineering properties and those of the Thermal-Shock Resistance Factors reported here also reflected the anisotropic behavior of a built-up roofing membrane constructed from organic and asbestos base felts. The difference in value of these properties between the "machine" (longitudinal) and the "across machine" (transverse) directions of both the organic and asbestos based felts appeared to be sufficiently large as to result in differences in performance in field service. Cullen described the relation between felt orientation and the frequency of tension tearing of built-up roofs in field service as a splitting which generally occurred parallel to the machine direction of the felt [2].

The samples prepared with glass based felts, for all practical purposes, exhibited isotropic behavior in respect to strength properties and Thermal-Shock Resistance Factors.

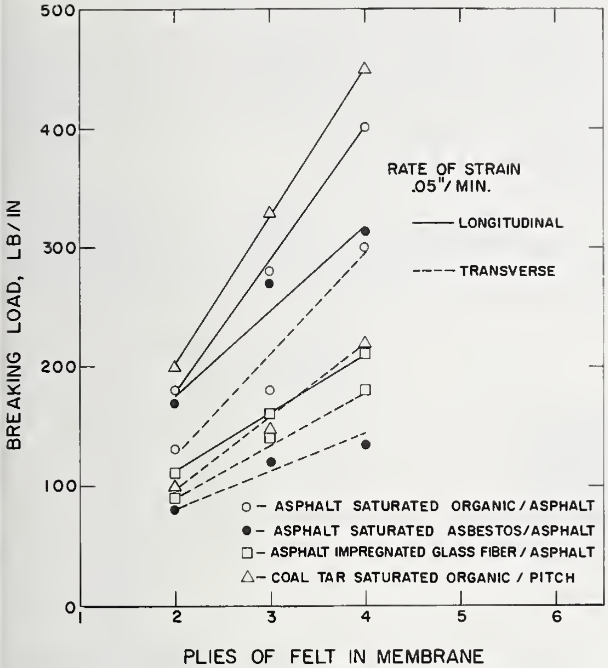

FIGURE 3. *Breaking load of built-up roofing membranes at 0 °F.*

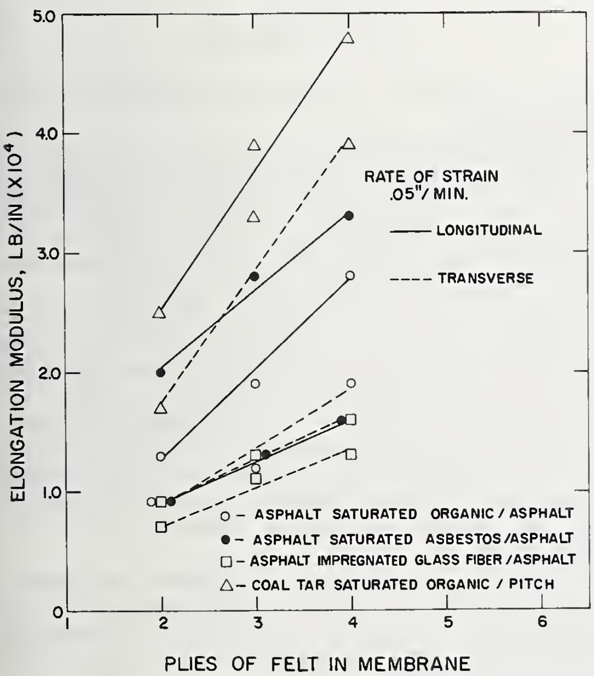

FIGURE 4. *Elongation modulus (initial tangent) of built-up roofing membranes at 0 °F.*

4.2. Relation Between Values of Thermal-Shock Resistance Factors and Performance in Field Service

The effective service life of a bituminous built-up roofing system depends to a large extent on the initial properties of the waterproof membrane, as well as on the retention of these properties during long periods (20 years or more) of exposure in service. The results of this investigation not only showed that the properties of various roofing membranes changed with exposure, but also indicated the type of changes which may be expected upon exposure to the elements. In this connection, a marked decrease in values of the breaking loads of those membranes exposed in service with some exceptions, was observed. An increase in values of both the elongation modulus and the linear thermal expansion was also indicated by a comparison of the results obtained on field samples and those obtained on the laboratory prepared specimens. When the values obtained during the testing procedure on the exposed specimens were substituted in eq (1), it was found that the Thermal-Shock Resistance Factors of the weathered samples were considerably lower than those obtained for the unweathered samples. It is extremely important to note here that no data were available on the original properties of the samples obtained from the field. Nevertheless, because of the similarity of construction and composition of the built-up field samples with those prepared in the laboratory, the following broad assumptions seem to be valid at this time.

The values for the Thermal-Shock Resistance Factors of coal-tar-pitch, organic felt membranes, although initially lower than those of the other samples included in the program, exhibited the least change when exposed under service conditions. On the other hand, the factors for the asphalt, organic felt membranes show the greater decrease in the values followed by the asphalt, glass felt membranes. Unfortunately, samples of the asphalt, asbestos felt membrane exposed to service conditions were not made available under the project.

If these data were applied to evaluate effective service life, they would indicate that, initially, the coal-tar-pitch, organic felt built-up roof membranes are more vulnerable to thermally induced forces than the asphalt, organic or the asphalt, glass combinations. However, as the weathering process proceeds, the difference in susceptibility to these forces between the coal-tar-pitch and aspaltic products is substantially reduced.

Samples were obtained from five built-up roofs each of which had exhibited tension splits in service attributed in part to thermally induced forces, while samples were obtained from two roofs exhibiting no such failures. In each of the five cases where splitting was reported, the length of the splits were parallel to the machine direction of the felt, without exception. This behavior was not unexpected, since previous field experiences have indicated that a relation exists between felt orientation and splitting failures [2]. Further, when the values for the Thermal-Shock Resistance Factors are considered in respect to felt orientation in the membrane, the "across machine" direction appears to be the most vulnerable to splitting failure.

In summary, the results of this study indicates that an apparent relation exists between the incidence of splitting failure in a membrane and the values of the Thermal-Shock Resistance Factor as given in table 4. Further, a comparison of results obtained in the laboratory and of observations of effective service life of built-up roofing systems in the field, confirm our opinion that the higher the Thermal-Shock Resistance Factor, the more resistant a membrane will be to failure due to thermally induced forces.

TABLE 4. *Relation between values of thermal shock-resistance and splitting failures observed under service conditions*

Felt (bitumen)	No. plies	Age yr.	Thermal shock-resistance factor (transverse direction)		
			Source	Membrane exhibiting tension splits	No evidence of tension splits
Organic (asphalt)	3	6	Rockford, Ill.		500
	3	22	Kansas City, Mo.	260	
	4	8	Waterloo, Iowa	350	
Glass (asphalt)	3	9	Omaha, Nebr.	350	
Organic (coal-tar)	3	12	Rockford, Ill.	100	
	4	20	Waterloo, Iowa		500
	4	25	Kansas City, Mo.	230	

5. Comments

Although all the pertinent properties of built-up membranes were not demonstrated experimentally in this program, it is believed that the thermal shock concept which is proposed may be useful in predicting the performance of built-up roofing membranes in respect to properties, roof design, and the environment in which the roofing system is expected to serve.

The authors' experience over many years with the performance of built-up roofings in service had indicated that many failures can be attributed to factors other than thermally induced forces with which this paper deals. Therefore, this paper should not be construed to imply that other factors as mechanically induced stresses, moisture migration, wrinkle cracking, flashing failures, and chemical degradation are not important considerations in many bituminous built-up roofing failures.

Splitting failures attributed in part to thermally induced forces appeared to be more prevalent in climates where roofing membranes were exposed to larger and more rapid temperature changes especially at subfreezing temperature than in areas where temperatures were milder and more uniform. In order for a membrane to resist forces due to large temperature changes at subfreezing temperatures, it follows that a higher value for the Thermal-Shock Resistance Factor will be required than for the same membrane exposed to milder climates. This parameter is not reflected in the factor given in eq (1). Therefore, in order to take into account the temperature conditions of the roofing system's ambient environment into the Thermal-Shock Resistance Factor, it is proposed that addition of another factor to the right side of eq (1) be made. Since thermally induced shrinkage failures are associated with low (subfreezing) and changing temperatures, the factor should take into account the temperatures experienced by a built-up roofing membrane in the area where the roof is exposed. Equation (1) may now be written:

$$TSRF_2 = \frac{S}{M\alpha} \cdot \frac{1}{\Delta tm} \tag{2}$$

where: $\Delta tm = 32$ °F minus (temperature of the membrane).

The membrane temperature at any one time will be influenced by a number of factors. These include the thermal characteristics of the roofing system, the inside temperature of the structure, the ambient temperature, the wind conditions, and the presence of moisture, water or snow.

Equation (2) approximates the ratio of the ultimate elongation of the membrane to the thermal contraction that occurs under the particular environmental conditions to which the membrane is subjected. As mentioned previously, the ratio S/M approximates the ultimate elongation. The thermal contraction equals the average coefficient of linear thermal expansion multiplied by the actual change in temperature of the membrane.

Based on the foregoing comments the authors feel there is a need for investigations of the engineering behavior of the whole roof assembly and the interrelationship of its components under different thermal exposures.

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6. References

[1] G. N. Moseley, built-up roofing tension splits, The Journal of the Building Research Institute **1,** No. 6, 31 (Nov.–Dec. 1964).

[2] W. C. Cullen, Effects of thermal shrinkage on built-up roofing, NBS Mono. No. 89 (1965).

[3] W. C. Cullen, Solar heating, radiative cooling and thermal movement—Their effects on built-up roofing, NBS tech. Note 231 (Dec. 1963).

[4] P. M. Jones, Recent research on bituminous materials, ASTM STP–347 Am. Soc. Testing Mats. (1963).

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