NATIONAL BUREAU OF STANDARDS REPORT

9356

THERMAL-SHOCK RESISTANCE FOR

BITUMINOUS BUILT-UP ROOFING MEMBRANES -

ITS RELATION TO SERVICE LIFE

by

William C. Cullen and Thomas H. Boone

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Materials and Composites Section
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Institute for Applied Technology

Sponsored by

Office of the Chief of Engineers
Department of the Air Force
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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 [3] to predict the ability of a built-up membrane to tolerate, without rupture, the forces induced by such temperature changes [4].

The higher the breaking load, the lower the apparent linear thermal expansion coefficient and the lower the modulus of elongation the more resistant the membrane will be to rupture under thermal changes. These parameters were combined in a Thermal-Shock Resistance Factor given by the following equation (1)

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

where

$TSRF_1$ = Thermal-Shock Resistance Factor

S = Breaking load, lb/in[2/]

M = Modulus of Elongation (initial tangent), lb/in[2/]

α = Coefficient of linear thermal expansion

The development of the Thermal-Shock Resistance Factor has been reported, and values for three conventional built-up membranes were given at temperatures of -30°F (-34.4°C), 0°F (-17.8°C), 30°F (-1.1°C), and 73°F (22.8°C) [6].

1/ Figures in brackets refer to references presented at the end of this paper.

2/ The breaking loads and moduli of elongation are expressed in pounds per inch width of membrane since a previous study [5] had shown that the effect of the bonding bitumen on the strength characteristics of the membrane are negligible. The elongation moduli are the slopes of the initial tangent to the load-strain curves.

2. EXPERIMENTAL

2.1 Materials and Specimen Preparation

2.1.1 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.

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 25-30 lb per 100 sq. ft., which is comparable to that obtained in good roofing practice. The laboratory prepared specimens were cut into a dumbbell-shaped according to a procedure developed at the National Bureau of Standards [6]. Figure 2 shows the die, the test specimen, and a cross section of the test specimen.

2.1.2 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 of roof rupture, samples were taken near the failure.

Information of 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 3 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 strengths 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 inches. A straining rate of 0.05 inches per minute (1.1% per minute) was used in each determination.

2.3 Linear Thermal Expansion Coefficients

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

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 apparent linear thermal expansion coefficient for the laboratory prepared and field obtained samples were calculated from data obtained over a temperature range of 30 to -30°F (-1.1°C 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.

Figure 4 shows that the breaking load in tension for a multiple-ply roofing specimen increased in proportion to the number of plies of felt in the membrane. Further, the character of the reinforcing felt had a marked effect on the values of the breaking loads. Figure 5 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 coefficient of 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 many be concluded from the data 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 coefficients in respect to the orientation of the felt in a built-up membrane has been report [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. 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.

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

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 strength properties of the waterproof membrane, as well as on the retention of these properties during long periods 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 expansion coefficient was also indicated by a comparison of the results obtained on field samples and those obtained on the laboratory prepared specimens. When the values of the properties of the weathered samples were substituted in equation (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 should be noted here that no data were available on the original properties of the samples obtained from the field. However, because of the similarity of construction and composition of the built-up field samples with those fabricated 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 submitted under the project.

If these data were applied to predict 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 is susceptibility to these forces between the coal-tar-pitch and asphaltic products in 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.

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.

Splitting failures attributed in part to thermally induced forces appear to be more prevalent in cold climates where roofing membranes were exposed to larger and more rapid temperature changes than in areas where temperatures were more uniform. In order for a membrane to resist these failures due to large temperature changes at sub-freezing 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 concept is not included in the factor given in equation (1). Therefore, in order to reflect the temperature conditions of the roofing system's environment into the Thermal-Shock Resistance Factor, it is proposed that the inclusion of another term to the right side of equation (1) be made. Since thermally induced shrinkage failures are associated with low and changing temperatures, the term should take into account only temperatures below 32°F and possible extreme changes which may occur in the climate where the roof is exposed. Equation (1) may now be written

$$TSRF_2 = \frac{S}{M\alpha} \cdot \frac{1}{\Delta t} \qquad (2)$$

where: t = 32°F - (minimum mean daily temperature, January).

The relative position of a bituminous built-up membrane in a roofing system will also influence its effective service life. It has been demonstrated experimentally that bituminous built-up membranes placed over insulation were subject to greater temperature changes than similar membranes placed over more dense substrates [4]. It has also been observed that tension splits attributed in part to thermally induced forces occur more frequently in membranes placed over substrates having high thermal insulating values. Therefore, it appears that the ability of components of the roof system to conduct heat to and away from the roofing membrane will, by regulating the amount and rate of temperature change of the membrane, affect the service life of the membrane. The thermal diffusivity of the substrate would appear to be a relevant factor in the Thermal-Shock Resistance Factor and may be included by rewriting equation (2)

$$TRSF_3 = \frac{S}{M\alpha} \cdot \frac{1}{\Delta t} \cdot \frac{k}{pd}$$

where K = thermal conductivity of the substrate
p = specific heat of the substrate
d = density of the substrate.

Based on the foregoing comments the authors suggest the above equation (3) as a possible useful revision of the Thermal-Shock Resistance Factor and feel that it should be tested by further investigations of the engineering behavior of the whole roof assembly and of the interrelationship of its components under different thermal exposures.

6. ACKNOWLEDGMENT

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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	1/
Coal-tar Saturated Organic Felt	D227

1/ "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.

Table 2. Properties of Laboratory Prepared Built-Up Membranes at 0°F

Felt (bitumen)	No. Plies	Direction 1/	Break Load (S) 2/ lb/in	Elong. Mod. (M) 2/ lb/in	Appar. Lin. Therm. Exp Coeff. $(°F)^{-1}$	Thermal Shock Factor
Organic (asphalt)	2	L	180	$1.3x10^4$	$10x10^{-6}$	1350
		T	130	$.9x10^4$	$17x10^{-6}$	850
	3	L	280	$1.9x10^4$	$10x10^{-6}$	1500
		T	180	$1.2x10^4$	$24x10^{-6}$	650
	4	L	400	$2.8x10^4$	$11x10^{-6}$	1300
		T	300	$1.9x10^4$	$21x10^{-6}$	750
Asbestos (asphalt)	2	L	170	$2.0x10^4$	$10x10^{-6}$	850
		T	80	$.9x10^4$	$26x10^{-6}$	300
	3	L	270	$2.8x10^4$	$8x10^{-6}$	1200
		T	120	$1.3x10^4$	$30x10^{-6}$	300
	4	L	310	$3.3x10^4$	$11x10^{-6}$	850
		T	130	$1.6x10^4$	$32x10^{-6}$	250
Glass (asphalt)	2	L	110	$.9x10^4$	$20x10^{-6}$	620
		T	80	$.7x10^4$	$20x10^{-6}$	600
	3	L	160	$1.3x10^4$	$22x10^{-6}$	540
		T	140	$1.1x10^4$	$35x10^{-6}$	360
	4	L	210	$1.6x10^4$	$20x10^{-6}$	660
		T	180	$1.3x10^4$	$22x10^{-6}$	610
Organic (coal tar)	2	L	200	$2.5x10^4$	$22x10^{-6}$	370
		T	100	$1.7x10^4$	$33x10^{-6}$	190
	3	L	330	$3.9x10^4$	$25x10^{-6}$	330
		T	150	$3.3x10^4$	$42x10^{-6}$	110
	4	L	450	$4.8x10^4$	$27x10^{-6}$	350
		T	220	$3.9x10^4$	$42x10^{-6}$	140

1/ L - Longitudinal (with machine)
T - Transverse (across machine)
2/ Average of three specimens
3/ Temperature Range +30°F to -30°F

Table 3. Properties of Built-Up Roofing Field Samples at 0°F

Felt (bit.)	No. Plies	Age Yrs.	Source	Dir.[1/]	Break Load (S) [2/] lb/in	Elong. Mod. (M) [2/] lb/in	Appar. Lin. Therm. Exp. Coeff. (α) [3/] $(°F)^{-1}$	Thermal Shock Factor
Organic (asphalt)	3	6	Rockford, Ill.	L	240	$4.5x10^4$	$16x10^{-6}$	750
				T	140	$4.7x10^4$	$41x10^{-6}$	500
Organic (asphalt)	3	22	K. C., Mo.	L	220	$2.3x10^4$	$15x10^{-6}$	620
				T	130	$1.6x10^4$	$30x10^{-6}$	260
Organic (asphalt)	4	8	Waterloo, Iowa	L	230	$1.4x10^4$	$25x10^{-6}$	650
				T	80	$1.1x10^4$	$23x10^{-6}$	350
Glass (asphalt)	3	9	Omaha Nebr.	L	90	$1.8x10^4$	$20x10^{-6}$	450
				T	80	$1.2x10^4$	$19x10^{-6}$	350
Organic (coal-tar)	3	12	Rockford Ill.	L	210	$3.8x10^4$	$20x10^{-6}$	300
				T	70	$2.0x10^4$	$31x10^{-6}$	100
Organic (coal-tar)	4	20	Waterloo Iowa	L	270	$5.1x10^4$	$9x10^{-6}$	550
				T	200	$2.5x10^4$	$16x10^{-6}$	500
Organic (coal-tar)	4	25	K. C., Mo.	L	490	$5.1x10^4$	$13x10^{-6}$	560
				T	260	$4.9x10^4$	$23x10^{-6}$	230

1/ L - Longitudinal (with machine)
T - Transverse (across machine)
2/ Average of three specimens
3/ Temperature Range +30°F to -30°F

Table 4. Relation Between Values of Thermal Shock-Resistance and Splitting Failures Observed Under Service Conditions

Felt (bitumen)	No. Plies	Age Yrs.	Source	Thermal Shock-Resistance Factor (Transverse Direction): Membrane Exhibiting Tension Splits	Thermal Shock-Resistance Factor (Transverse Direction): 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	

CAPTIONS FOR FIGURES

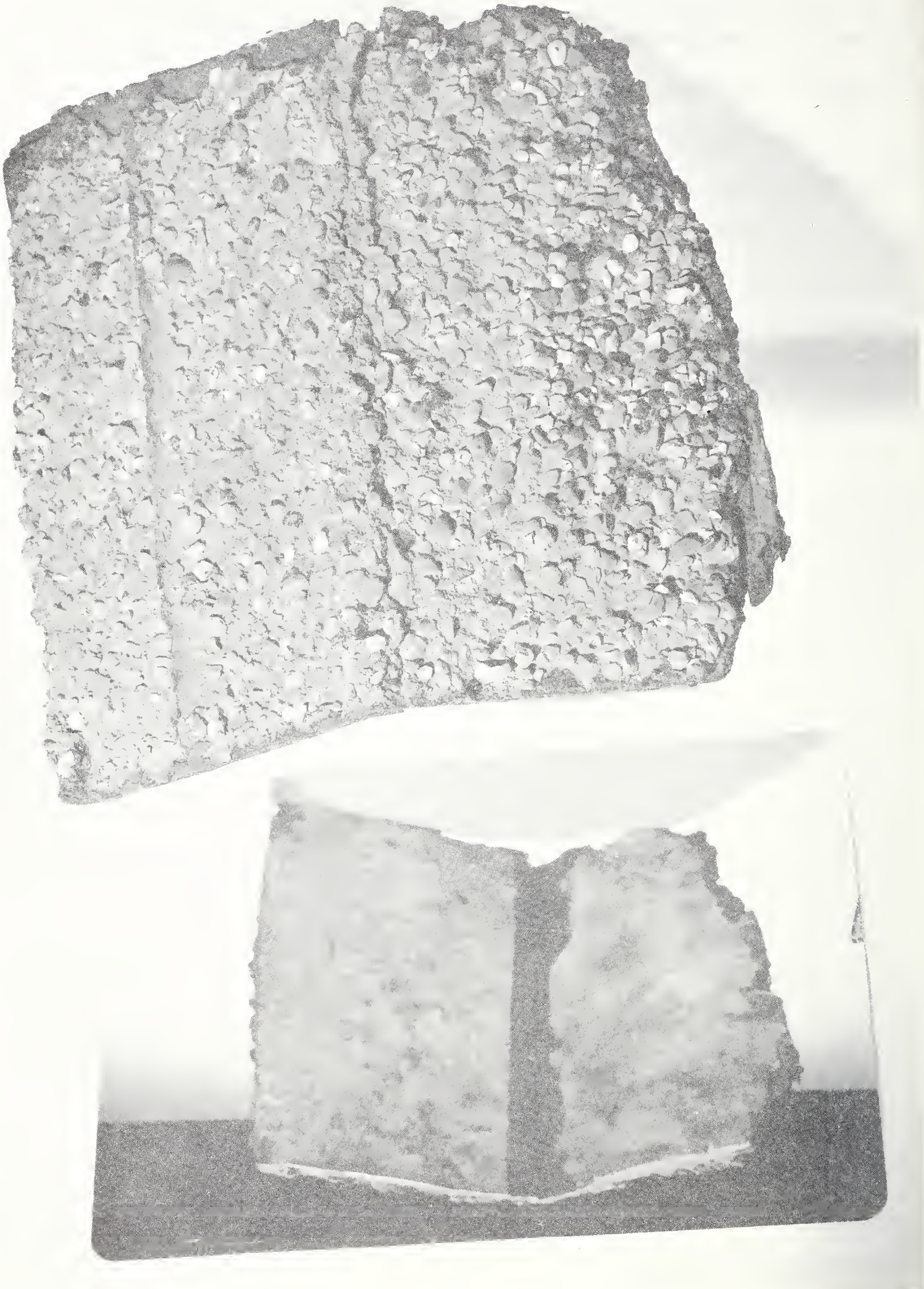
Figure 1. Roof sample taken from field. Note membrane split.

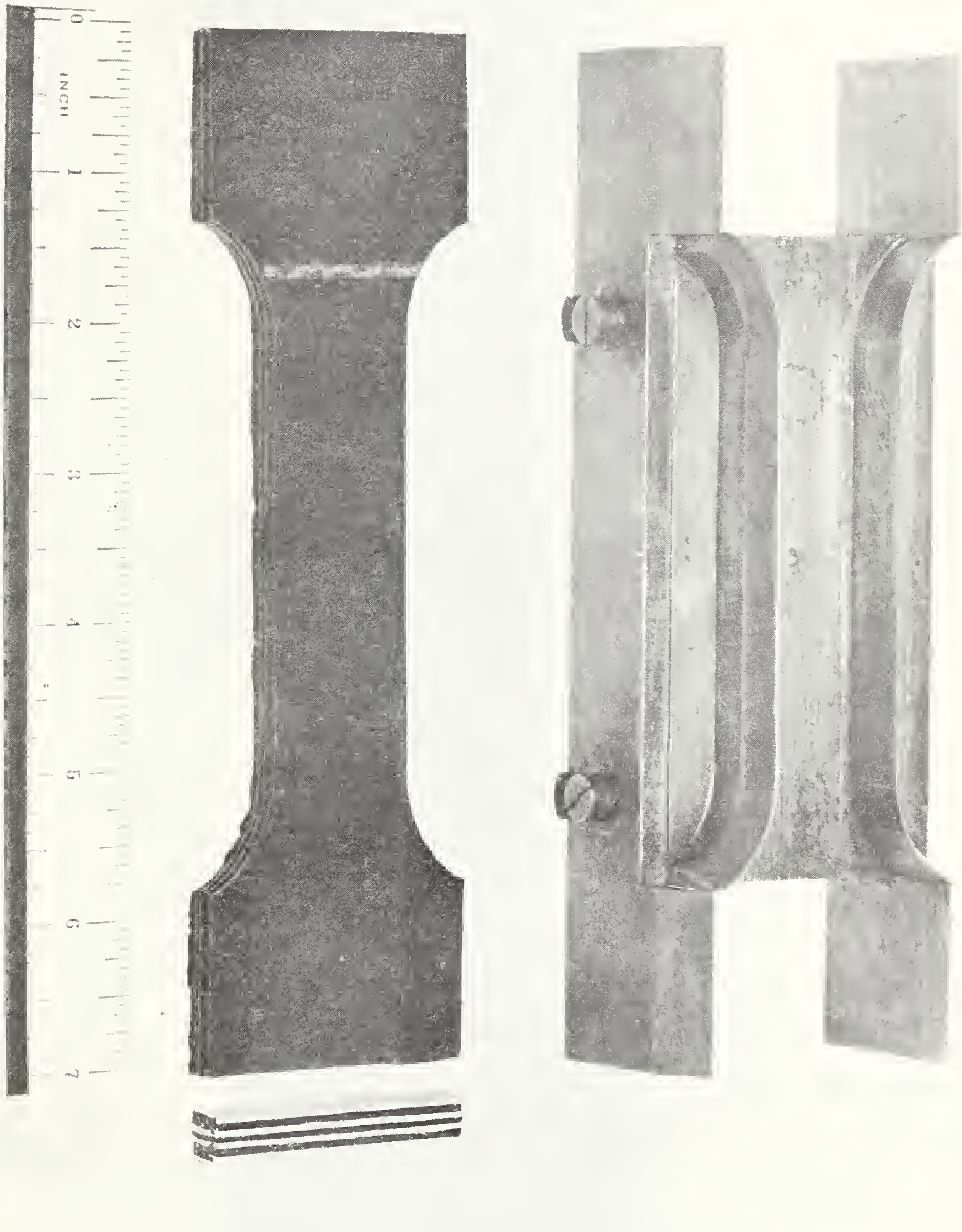
Figure 2. Cutting die, four-ply built-up roofing specimen and cross section of membrane.

Figure 3. A prepared test specimen of a membrane taken from the field after nine years exposure.

Figure 4. Breaking load of built-up roofing membranes at 0°F.

Figure 5. Elongation modulus (initial tangent) of built-up roofing membranes at 0°F.





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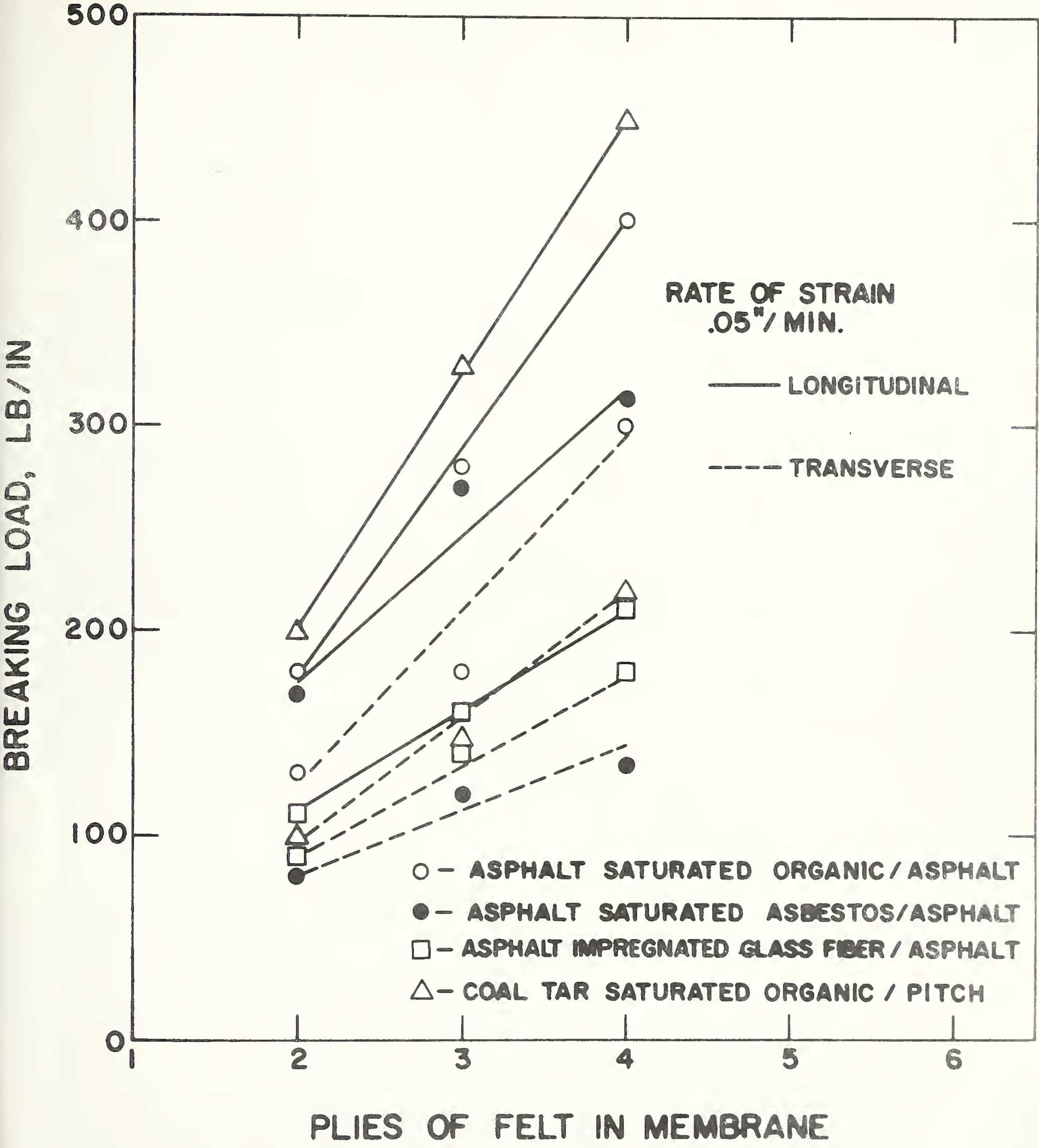

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BREAKING LOAD, LB/IN
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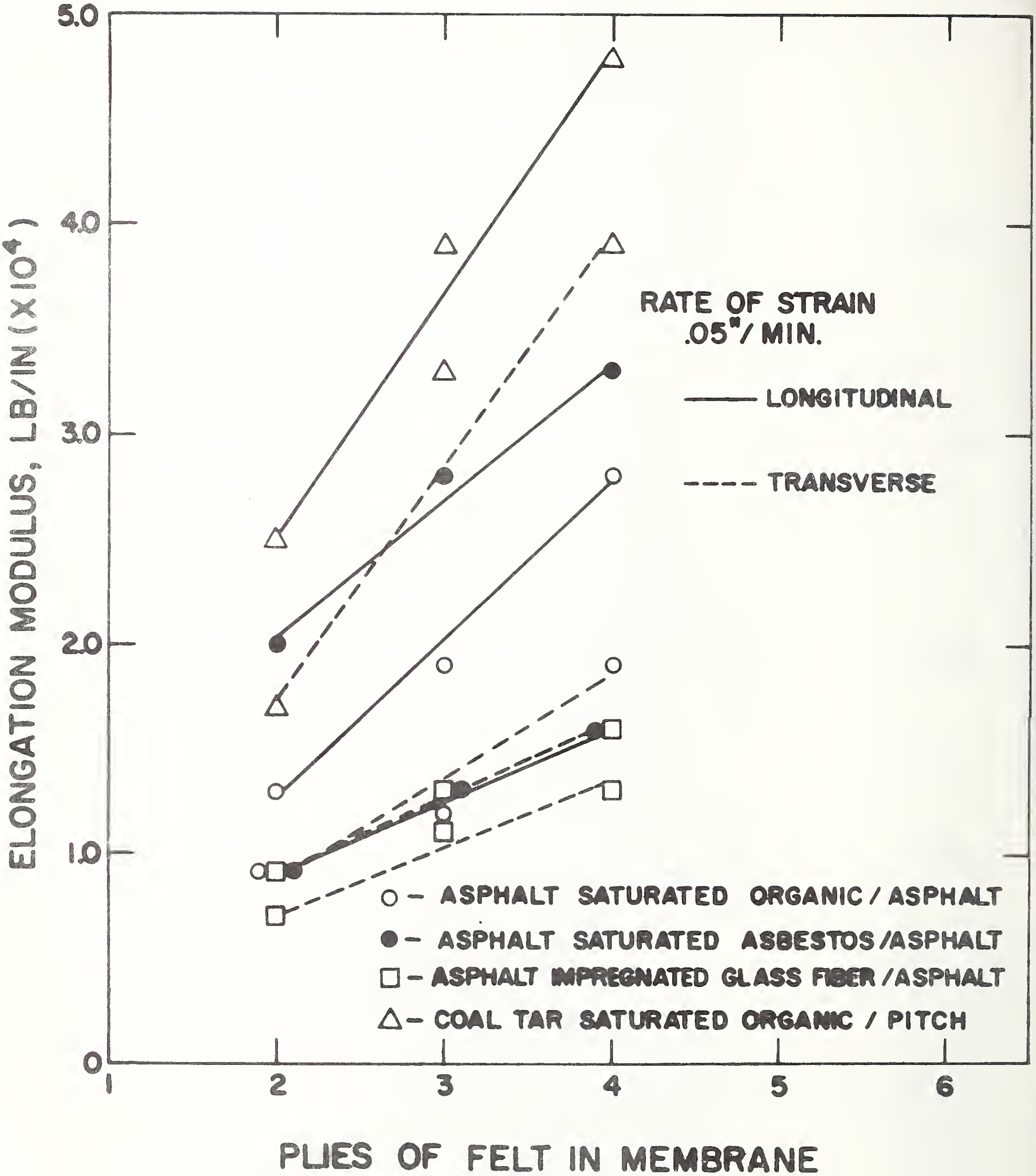
PLIES OF FELT IN MEMBRANE
RATE OF STRAIN
.05"/ MIN.
LONGITUDINAL
TRANSVERSE
○ – ASPHALT SATURATED ORGANIC / ASPHALT
● – ASPHALT SATURATED ASBESTOS/ASPHALT
□ – ASPHALT IMPREGNATED GLASS FIBER / ASPHALT
△ – COAL TAR SATURATED ORGANIC / PITCH



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ELONGATION MODULUS, LB/IN (X10⁴)
PLIES OF FELT IN MEMBRANE
RATE OF STRAIN
.05"/ MIN.
LONGITUDINAL
TRANSVERSE
○ – ASPHALT SATURATED ORGANIC / ASPHALT
● – ASPHALT SATURATED ASBESTOS /ASPHALT
□ – ASPHALT IMPREGNATED GLASS FIBER /ASPHALT
△ – COAL TAR SATURATED ORGANIC / PITCH

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