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Preliminary Performance Criteria for Bituminous Membrane Roofing

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Preliminary Performance Criteria for Bituminous Membrane Roofing

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Contents

Preliminary Performance Criteria for Bituminous Membrane Roofing

Robert G. Mathey and William C. Cullen

This report is the first in a series of publications on performance criteria for built-up roof membranes. The development of a performance approach to bituminous built-up roof membranes is described and preliminary performance criteria are recommended. A number of test methods have been developed in order to obtain data to evaluate roofing membranes against the recommended criteria. Twenty attributes that effect the performance of roof membranes under service conditions are identified and laboratory tests are described for measuring the engineering properties of the membrane that pertain to many of these attributes. A level of performance is recommended for nine of the identified performance attributes.

Key words: Bituminous roof membranes; performance attributes; performance criteria; physical and engineering properties; test methods.

SI Conversion Units

In view of present accepted practice in the United States of America in the roofing technology area, common U.S. units of measurement have been used throughout this paper. In recognition of the position of the USA as a signatory to the General Conference of Weights and Measures, which gave official status to the International System of Units (SI) in 1960, we assist the readers interested in making use of the coherent system of SI units by giving conversion factors applicable to U.S. units used in this paper.

Length
1 in = 0.0254* meter
1 ft = 0.3048* meter
Area
1 in^2 = 6.4516* $\times 10^{-4}$ meter^2
1 ft^2 = 0.09290 meter^2
Force
1 lb (1bf) = 4.448 newton
Stress
1 psi = 6895 newton/meter^2
Frequency
1 cycle per second = 1* hertz

* Exactly

1. Introduction

The majority of low-slope roof constructions in the United States consist of bituminous built-up roof systems. This term is used to describe roofs in which the waterproofing membrane is installed in layers of reinforcing felts which are adhered together with a bituminous material. The membrane is generally installed over insulation and is sometimes applied directly to the roof deck.

In the United States, the desired properties and characteristics of bituminous membrane built-up roofs have been traditionally described by prescriptive types of specifications for the individual materials which comprise the roofing membrane. The performance of the bituminous membrane itself has been considered only from a practical viewpoint, that is, observation of its durability under in-service conditions. The specification of materials imposes constraints on the design of roofing systems, manufacture of roofing products and the application of roofing materials. Poor performance of roofs has often been attributed to these constraints on the design, manufacture and application process. Prescriptive specifications inhibit new product development and the introduction of innovative systems for membrane roofing. The intent of this investigation has been the development of a performance approach to the evaluation of bituminous membrane roofing which is believed to be needed to overcome the traditional road blocks that prescriptive specifications of roofing materials present.

This research at the National Bureau of Standards was carried out to identify and describe quantitatively the attributes which would be required of bituminous membrane roofing to assure their adequate performance in the varied climates of the United States. This paper presents the results of that research and preliminary performance criteria for bituminous membrane roofing.

2. Bituminous Membrane Roofing in the United States

Since the turn of the twentieth century, bituminous built-up roofing membranes have been used in the United States to protect buildings, their contents and occupants from the weather. In general, these membranes have provided satisfactory service, but in many instances, they have been the source of problems for the manufacturer, designer, applier and the user. The problems have been attributed, in part, to such obvious causes as poor design, inadequate specifications and improper workmanship. Certainly these factors can be controlled to some extent by education which would insure the use of proper specifications and by construction inspection which will insure good workmanship. Information concerning adequate specifications and proper construction practices is available at the current state-of-the-art of bituminous roofing technology in the United States. However, for various and sundry reasons this information is sometimes ignored and often not known by those who design, apply and use roof systems.

The most common type of bituminous membranes consist of two to five plies or layers of felt or fabric which is saturated or impregnated and sometimes coated with a bituminous material during manufacture. The felts may be composed of felted organic materials, asbestos fibers or fibrous glass. The bituminous material used as saturant and coating may be either a petroleum asphalt or coal tar pitch. In practice, the felts are adhered together with petroleum asphalt or coal tar pitch during application on the roof. Frequently, the membrane is surfaced with gravel or slag which is embedded in hot bitumen.

The felts and bitumen which comprise the bituminous built-up membrane are described by prescriptive specifications issued by manufacturers, the Federal Government or recognized standard-making bodies such as the American Society for Testing and Materials. Roofing felts must satisfy certain physical requirements such as the nature of the felt including its weight, percent saturation, flexibility and tensile strength. Roofing bitumens (asphalt and coal tar pitch) are frequently described by empirical characteristics such as softening point, penetration and ductility.

The application specification defines the kind and number of plies or layers of felt as well as the type and amount of bitumen to be used between the plies. This is the bituminous built-up membrane specification currently used in the United States. In spite of over 70 years use, nowhere are the required properties of a membrane identified or specified quantitatively. In fact, criteria for the built-up membrane do not exist even though there are about 30 million squares [1] of bituminous built-up roofing applied each year in the United States alone. The consequences of the unavailability of criteria are considerable and expensive as evidenced by the premature failures of many new types of roof membranes which should not have been marketed. Further, the lack of criteria probably represents the largest single constraint to the introduction of new and innovative systems into the roofing industry. The consequences become manifest when modifications of conventional systems or new membrane systems are introduced. Invariably, unforeseen problems arise causing failure of the membrane necessitating its replacement. The problems could be substantially reduced and perhaps eliminated if criteria for acceptable bituminous membranes were developed and made available to guide the developer or innovator. The development of adequate criteria for membrane roofing will represent a great step forward in elevating the art of roofing to a scientific basis.

The research reported in this paper was restricted to the development of criteria and test methods for bituminous built-up membrane roofing. Since the roof membrane is used in conjunction with one or more components of the total roof assembly (such as the structural deck, vapor barrier and insulation) the contribution of the various components, acting alone or in concert with others, to the performance of the roof membrane, must be dealt with. Therefore, the forces attributed to these interactions and those generated by the ambient environment have been taken into consideration when levels were defined for criteria for the bituminous built-up membrane. For a comprehensive discussion of the built-up roofing system, including the four interacting components, the reader is referred to a treatise on the subject prepared by Griffin [1]. [2]

[1] One square equals one hundred square feet.

[2] Figures in brackets refer to literature references given in section 8.

3. Performance Approach

The major research goal is the development of performance criteria which contains quantitative definitions of a roof membrane's overall ability to perform under service conditions. In order to establish valid and acceptable criteria, the past performance of roof membranes which have served satisfactorily must be used as a point of reference or basis for developing the criteria. An important intent of the performance approach is to provide a basis for evaluating roofing membranes with reasonable assurance that the membrane will perform satisfactorily over its intended use as well as, the ambient exposure climate of the roofing membrane. In depth consideration of weather conditions was not considered in the development of the preliminary performance criteria. The value of any criterion may be set according to climate, roof design and expected life of the building.

The performance statements presented in this report consist of a requirement which is qualitative in nature and describes what the membrane is to accomplish. This is followed by a criterion or criteria which expresses quantitatively, the acceptable levels for adequate performance. An evaluative technique or test method is then referenced or described by which compliance with the stated criteria can be tested. Finally, a commentary is helpful in providing an explanation of the reason for, and the intent of, the stated criteria.

The successful implementation of the performance approach to the design, manufacture, and installation of bituminous membrane roofing will represent a significant achievement in the application of bituminous roofing technology. In addition to providing guidance for the development of better and more economical bituminous membranes, the performance approach will pave the way for both new products and innovative systems which are so badly needed by the roofing industry.

4. Performance Attributes

Observations made during field surveys of bituminous built-up roofing throughout the fifty states in the U.S.A. and territories of Puerto Rico and Guam over many years have led to the identification of certain problems associated with the behavior of bituminous built-up membrane roofing systems. The severity of the problems ranged from minor, such as small adhesion problems, to catastrophic such as severe membrane splitting and costly membrane slippage. Blistering, wrinkling, and wrinkle cracking of the membrane were among the more common defects observed. Although frequently these defects were not evidenced by the immediate failure of the waterproofing systems, they resulted in shortening the expected life of 20 or more years of a built-up roof by a significant amount. Thermal splitting or cracking of the membrane, slippage between plies of the felt and wind blow-offs occurred less frequently, but generally resulted in costly and immediate repairs or sometimes in the removal and replacement of the complete roof system. In the course of the field surveys, good performing membranes were compared to those that deteriorated more rapidly than expected and the reasons for the performance were explored. Samples of roof membranes were brought into the laboratory, where they were examined and their properties were measured and related to field behavior.

As a result of these long-term observations, some twenty attributes have been identified which are believed to have significant impact on the total performance of the roofing system under in-service conditions. It is important to note here that a maximum value of the level of performance for any one attribute is not necessary to quantify performance adequately. Rather, a balance of values among the several attributes is more desirable, so long as they remain within levels of acceptable performance.

The following attributes which were identified for laboratory study:

1. Tensile Strength—The membrane is not expected to perform as a structural member, but it must have sufficient strength to resist stresses caused by internal and external forces imposed on it during use.

2. Thermal Expansion—Roofing membranes are exposed to rather large and often rapid temperature changes. The thermal expansion coefficient should not be so large as to cause deleterious effects on the membrane under service conditions.

3. Flexural Strength—As stated in the case of tensile strength, the membrane is not expected to perform as a structural member. However, it must have sufficient flexural strength to resist forces such as those caused by wind, moving wheel loads, foot traffic, thermal and moisture movement and other forces causing bending of the membrane, particularly during cold weather.

4. Tensile Fatigue Strength—Repeated stresses caused by thermal, moisture and building movement should be resisted by the membrane. The strength of the membrane should not be significantly reduced by the application of repeated forces.

5. Flexure Fatigue Strength—Repeated stresses caused by wind uplift forces, vibrations, wheel loads, foot traffic and the like should be resisted by the membrane. The strength of the membrane should not be significantly reduced when subjected to repeated forces causing bending of the membrane.

6. Shear Strength—The membrane should withstand vertical punching shear forces from anticipated foot traffic and the other effects. Horizontal shear forces caused by different stress levels in the felts should not affect the integrity of the membrane.

7. Impact Resistance—Falling objects such as hailstones, tree limbs, tools, and the like, should be resisted by the membrane without causing penetrations or breaks in it.

8. Notch Tensile Strength—The tensile strength of the membrane should not be significantly reduced by stress concentration caused by imperfections or slightly damaged areas in the felts. At low temperatures, bituminous membranes have properties of brittle materials.

9. Moisture Effects on Strength—Moisture in the membrane resulting from the use of wet materials or the penetration by water or water vapor into the membrane can result in excessively high stresses in the membrane. These stresses caused by wetting and drying combined with thermal and other stresses must not exceed the strength of the membrane. Furthermore, appreciable loss in strength of the membrane may be attributed in some cases to the presence of moisture in the roofing system.

10. Creep—Membranes are often subjected to stress over long periods of time as a result of internal forces caused by thermal, moisture and building movement along with externally applied forces. The membrane should be able to withstand sustained stress without significant permanent deformation.

11. Ply Adhesion—Composite action of the membrane depends on sufficient adhesion of felts to each other by means of the between-ply bitumen. Blister formation can be reduced by eliminating voids bewteen plies where moisture can accumulate.

12. Abrasion Resistance—The membrane should withstand anticipated wearing away from wind-blown elements, traffic and other objects dragged across the roof.

13. Tear Resistance—The membrane should resist tearing or ripping when subjected to anticipated external and internal forces.

14. Pliability—For anticipated climatic conditions, the membrane should withstand, without rupture, repeated bending caused by forces imposed during service. Forces resulting from vibration, wind uplift, thermal, moisture and building movement can cause bending of the membrane. Pliability differs from flexural strength and flexural fatigue strength in that the flexibility of the membrane is of concern and not its strength or load carrying capacity. In general, the pliability of the membrane at the lowest anticipated temperature should be considered.

15. Permeability—The penetration of water or water vapor from either outside or inside should be prevented. Penetration of water vapor can result in condensation, decrease in insulation efficiency and other adverse effects, such as differential movement, deflection and rot of other system components.

16. Moisture Expansion—Not only can moisture cause a significant decrease in membrane strength and induce high stress in the membrane, but it can also cause an increase in length of the membrane. This length increase is generally not reversible and ridging results.

17. Weather Resistance—The membrane should withstand anticipated climatic conditions, such as solar radiation, moisture, pollutants, and the like without adverse effects on the performance of the roof system when exposed for its expected service life.

18. Wind Uplift Resistance—The membrane should withstand anticipated wind forces without adverse effects.

19. Fire Resistance—The membrane should provide a specified resistance against combustibility and flame spread.

20. Fungus Attack Resistance—Any appreciable reduction in performance or appearance resulting from decay should be prevented during the expected service life of the membrane.

5. Laboratory Research Program

The twenty performance attributes identified above were included in the plans of an experimental program which was aimed at developing test methods, measurement techniques and meaningful limits of acceptability of built-up roof membranes. A literature survey was conducted to determine the state-of-the-art of bituminous roofing technology and most importantly, to identify current tests for measuring performance of built-up roof membranes. The survey indicated that many new tests needed to be developed to measure the performance of built-up roofing, however, for some of the attributes, such as wind uplift resistance and fire resistance, available tests were considered adequate at this time. It is noted that a committee sponsored by the Building Research Advisory Board of the U.S. National Academy of Science, which was chaired by William C. Cullen, developed a list of performance characteristics similar to those developed in this investigation [2].

In the overall planning of the research program, emphasis was placed on small and large scale tests as well as on field studies. The small scale tests, however, comprised the major portion of the research program. The large scale tests were intended to supplement the small scale tests and to provide data on stresses and deformations that occur or develop during service conditions due to thermal and moisture changes. The large scale tests have not been conducted, however, future plans call for carrying out these tests. Field studies have been limited to the inspection of roof problems and recommendations or suggestions for their solution. The recommendations were based, in part, on laboratory tests of the field samples of roofing and the data were included in some of the small scale tests. Most data from the small scale tests, however, were derived from laboratory prepared samples.

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

Membrane designation	Materials	ASTM designation
	Bitumens:	
	Asphalt	D312, Type I
	Coal-tar pitch	D450, Type A
	Reinforcing felt:	
A	Coal-tar saturated organic felt	D227
B	Asphalt saturated organic felt	D226, 15 lb type
C	Asphalt saturated asbestos felt	D250, 15 lb type
D	Asphalt impregnated glass mat	D2178, Type I
E [a]	Asphalt impregnated glass mat	New product

[a] This type of asphalt impregnated glass mat was recently developed and therefore was not included in all the laboratory tests.

The small scale tests were carried out primarily on four types of 4-ply membrane, however, other types of membranes were also included in the test program. The materials used in the preparation of the membrane test specimens which were included in all the various tests are identified in table 1.

All of the various laboratory tests were carried out using 4-ply membranes designated as A, B, C, and D and some of the tests included membrane E. Limited tests were conducted using other types of membranes including both laboratory prepared and field specimens. Data are reported on the five types of membrane given in table 1.

When applicable, the test specimens conformed to standard size specimens such as those described in ASTM D–2523 [3]. Prior to fabrication of the small scale specimens, the moisture content of the felt was determined and properties of the bitumens ascertained. The thickness of the between-ply bitumen was controlled and measured for each specimen.

5.1. Results of Laboratory Tests

Laboratory tests were conducted to measure the performance of roofing with regard to the first seven attributes listed in section 4. The attributes are essentially mechanical properties of the membrane which include tensile strength, thermal expansion, flexural strength, shear strength, fatigue strength, and impact resistance. Preliminary performance criteria, including the seven attributes listed above and wind uplift resistance and fire resistance are presented in section 6.

A brief description follows for each of the completed laboratory tests along with some typical data.

5.1.1. Tensile Strength

Tension tests were conducted on 4-ply specimens by the procedure described in ASTM Standard D–2523 modified to meet the needs of the research. Specimens were elongated at a rate of 0.08 in/min. Tests were carried out at 73, 30, 0, and −30 °F in both the machine direction and cross-machine direction of the felts. An extensometer with a 2-in gage length was attached to the specimen at mid-length and load strain data were continuously recorded until failure occurred. The tensile strength and load strain modulus were considered in the preliminary performance criteria in section 6. The tensile strength and load strain modulus of the membranes are given in tables 2 and 3, respectively for the five different types of membranes. The values in the tables represent the average of 3 tests.

TABLE 2. *Tensile strength of membranes*

Type of membrane	Membrane designation	Tensile strength, lb/in							
		73 °F		30 °F		0 °F		−30 °F	
		L[a]	T[b]	L	T	L	T	L	T
Organic felt and coal tar	A	126	62	395	217	468	265	410	237
Organic felt and asphalt	B	141	60	396	186	506	267	592	283
Asbestos felt and asphalt	C	120	36	301	123	448	182	479	165
Glass felt (Type I) and asphalt	D	86	70	190	161	175	144	184	123
Glass felt (new product) and asphalt	E	202	159	510	408	448	365	372	301

[a] L denotes longitudinal or machine direction of felts.
[b] T denotes transverse or cross machine direction of felts.

TABLE 3. *Load-strain modulus of membranes*

Type of membrane	Membrane designation	Load-strain modulus × 10^4 lb/in							
		73 °F		30 °F		0 °F		−30 °F	
		L[a]	T[b]	L	T	L	T	L	T
Organic felt and coal tar	A	2.1	0.6	7.9	9.9	6.7	7.4	10.6	7.7
Organic felt and asphalt	B	2.7	1.1	4.1	1.6	5.7	3.6	9.1	6.8
Asbestos felt and asphalt	C	3.3	1.2	4.4	2.3	8.0	5.5	9.8	8.4
Glass felt (Type I) and asphalt	D	1.3	1.2	1.4	1.3	3.0	2.6	1.5	1.0
Glass felt (new product) and asphalt	E	2.5	2.2	2.7	2.2	2.8	2.2	2.6	2.4

[a] L denotes longitudinal or machine direction of felts.
[b] T denotes transverse or cross machine direction of felts.

5.1.2. Thermal Expansion

Four tests were investigated to measure thermal contraction or expansion of roof membrane samples. These tests included using a continuous recording extensometer; using quartz rods to support test specimens and make length change determinations; use of thermal mechanical analyzer; and by means of mechanical measurements using a Whittemore extensometer. A Whittemore extensometer is described in ASTM Standard C426 [4]. The Whittemore extensometer gave unquestionably the best results. It is relatively simple to use, gage points can be set rather easily, it gives accurate reproducible results and a fairly large number of specimens can be tested at one time. The data were also reproducible for field specimens and results of tests of comparable field and laboratory prepared specimens gave favorable agreement.

The lengths of test specimens as described in ASTM Standard D–2523 over a 5-in gage length were measured at 73, 30, 0, and −30 °F. The coefficients of thermal expansion for three temperature ranges for the membranes are shown in figure 1. The average values presented in figure 1 are listed in table 4.

The test method for measurement of thermal expansion developed at the National Bureau of Standards has been accepted as a proposal by ASTM and is published as proposed test for "Coefficient of Linear Thermal Expansion of Roofing and Waterproofing Membranes" in the 1974 Book of ASTM Standards, Part 15 [5].

Values of the coefficient of expansion, tensile strength and load strain modulus can be used to calculate the thermal shock factor. Cullen and Boone [6] reported on thermal-shock resistance for built-up membranes in 1967. Based on modification and extension of their earlier work, it is proposed that the thermal shock factor can be calculated as follows:

$$TSF = \frac{P}{M\alpha}$$

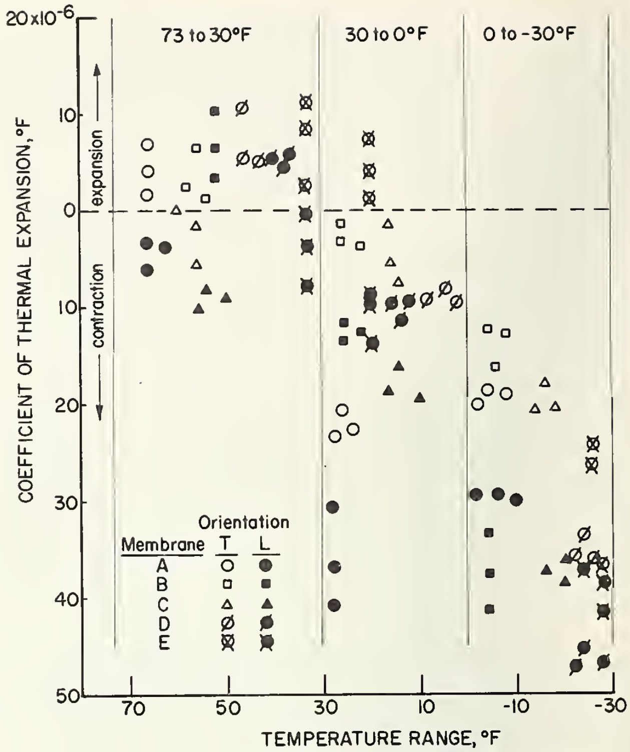

FIGURE 1. *Coefficients of thermal expansion for membranes for three temperature ranges.*

where,

TSF is the thermal shock factor
P is the tensile strength at 0 °F
M is the load strain modulus at 0 °F
α is the coefficient of expansion for the temperature range 0 to −30 °F.

Values of the thermal shock factor for five types of membranes are given in table 5. The thermal shock factor was computed using values of tensile strength, load strain modulus and coefficient of thermal expansion from table 2, 3, and 4, respectively.

TABLE 4. *Coefficients of thermal expansion for roof membranes*

Type of membrane	Membrane designation	Coefficient of thermal expansion °F⁻¹ temperature range [a]					
		73 to 30 °F		30 to 0 °F		0 to −30 °F	
		L [b]	T [c]	L	T	L	T
Organic felt and coal tar	A	−3.3	4.4	22.3	36.0	19.3	29.5
Organic felt and asphalt	B	−3.4	−6.6	2.7	12.6	13.9	37.4
Asbestos felt and asphalt	C	2.3	9.2	4.8	18.1	19.5	37.5
Glass felt (Type I) and asphalt	D	−7.1	−5.3	8.9	10.1	35.1	46.4
Glass felt (new product) and asphalt	E	−7.3	3.9	−4.2	10.7	29.0	39.0

[a] Values in table to be multiplied by 10^{-6}.
[b] L denotes longitudinal or machine direction of felts.
[c] T denotes transverse or cross machine direction of felts.

5.1.3. Flexural Strength

Flexural tests were carried out on five types of four-ply membrane samples at 73 and 0°F. The test specimens were of the type described in ASTM Standard D–2523. Built-up roofing membranes have essentially no stiffness, especially at room temperature. It was therefore necessary to have the ends of the specimen fixed for the flexural tests. A support frame was designed and fabricated which allowed the ends of the specimen to rotate at the supports. The load was applied by means of 1½- in diam half round steel bar at the midspan of the specimen. Flexural strength and maximum deflection of the membrane specimens are given in table 6 and table 7, respectively. These data represent the average value of three specimens tested for each type of membrane at each temperature.

TABLE 5. *Thermal shock factors for roof membranes*

Type of membrane	Membrane designation	Thermal shock factor, °F	
		L[a]	T[b]
Organic felt and coal tar	A	360	120
Organic felt and asphalt	B	640	200
Asbestos felt and asphalt	C	290	90
Glass felt (Type I) and asphalt	D	170	120
Glass felt (new product) and asphalt	E	550	420

[a]L denotes longitudinal or machine direction of felts.
[b]T denotes transverse or cross machine direction of felts.

TABLE 6. *Flexural strength of membrane specimen*

Type of membrane	Membrane designation	Maximum load at midspan, lb			
		73 °F		0 °F	
		L	T	L	T
Organic felt and coal tar	A	73	44	141	39
Organic felt and asphalt	B	48	33	143	43
Asbestos felt and asphalt	C	45	17	97	17
Glass felt (Type I) and asphalt	D	39	23	26	24
Glass felt (new product) and asphalt	E	164	126	159	132

TABLE 7. *Maximum deflection of membrane specimens*

Type of membrane	Membrane designation	Maximum deflection at midspan, in			
		73 °F		0 °F	
		L	T	L	T
Organic felt and coal tar	A	1.3	1.7	0.7	0.6
Organic felt and asphalt	B	1.2	1.0	0.8	0.6
Asbestos felt and asphalt	C	1.3	1.2	0.6	0.7
Glass felt (Type I) and asphalt	D	1.7	1.2	0.7	0.6
Glass felt (new product) and asphalt	E	1.6	1.4	0.7	0.8

5.1.4. Tensile Fatigue Strength

Tensile fatigue strength tests were carried out on four types of built-up roof membrane samples at 73 and 0 °F. The samples were of the type described in ASTM Standard D–2523. The felts in the sample membrane were oriented in the cross machine or transverse direction. Three sets of specimens of each type of membrane, were tested to failure. The rate of load application was 10 cycles per second (cps) for specimens tested at 73 °F and 15 cps for specimens tested at 0 °F. Data for tension fatigue tests at 73 °F are shown graphically in figure 2. The rate of load application has an effect on the number of cycles the specimens can withstand prior to failure. A major consideration in the selection of the load rate was the length of time to conduct the test.

The maximum forces applied to the three sets were approximately 80, 60, and 40 percent of the tensile strength of the membranes, respectively. The specimens were loaded in tension-tension so that the smaller force was 10 percent of the larger applied fatigue force.

A preliminary analysis of data of tensile fatigue tests at 0 °F indicated that the specimens tested at 80 percent of their tensile strength failed at considerably fewer number of cycles of force than when tested at room temperature. The specimens tested at 60 and 40 percent of their tensile strength failed in general at considerably more cycles of force at 0 °F than when tested at 73 °F.

5.1.5. Flexural Fatigue Strength

The same four types of membranes as described in the tensile fatigue tests were tested in flexural fatigue at 73 and 0 °F. Test specimens were the type described in ASTM Standard D–2523. The felts in the test specimens were oriented in the cross machine or transverse direction. The specimens

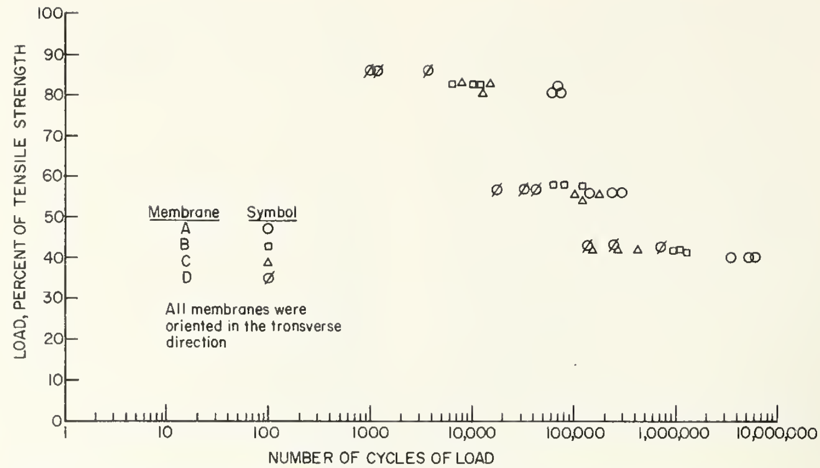

FIGURE 2. *Tensile fatigue strength of built-up roofing membranes tested at 73 °F.*

were tested in the same manner as in the flexural tests, except the specimens were subjected to repeated cycles of loading. The loading was controlled by the amplitude of the midspan deflection. The deflection amplitudes were 0.2, 0.15, and 0.125 in with the rates of loading 2, 3, and 4 cps, respectively for specimens tested at 73 °F. The decision was made to control the amplitude of the midspan deflection of the specimen as compared to controlling the load. Regardless of whether the force or amplitude was controlled, the other would vary during the test.

The data given in figure 3 shows the relationships between the midspan deflection and the number of cycles of load causing failure for specimens tested at 73 °F. A preliminary analysis of data of flexural fatigue tests at 0 °F indicated that specimens failed at considerably less cycles of force than when tested at room temperature except the organic felt-coal tar membranes tested at amplitudes of force of 0.20 and 0.12 in.

5.1.6. Shear Strength (punching)

Tests were carried out to determine the punching shear resistance of four types of built-up, four-ply membranes placed over five types of insulation. The punching shear tests were conducted at both 73 and 0 °F. The five types of insulation included foam glass, wood fiber, perlite board, fiberglass and plastic foam. The compressive strengths of the insulations were determined in order to compare

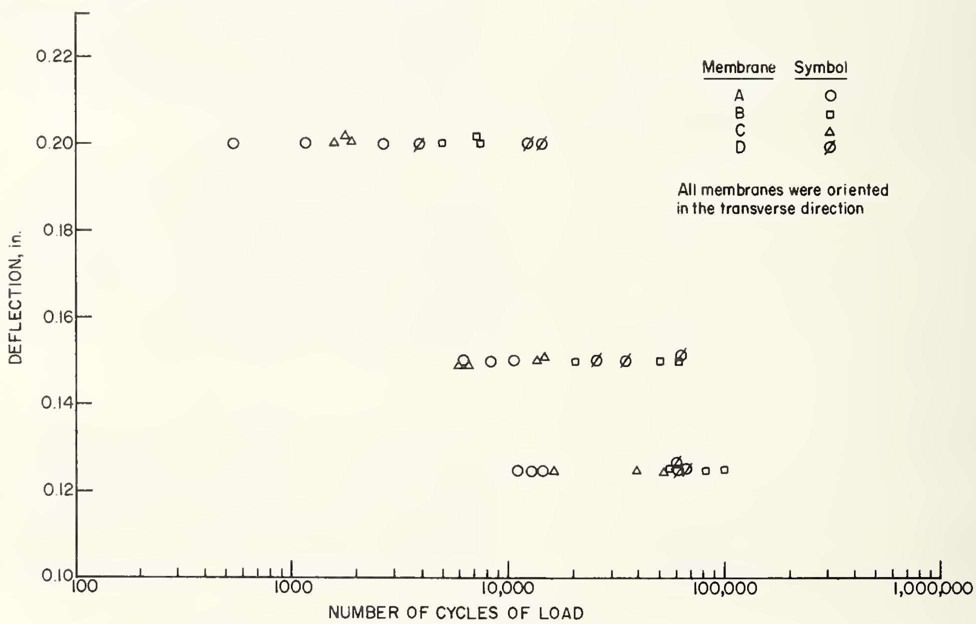

FIGURE 3. *Flexural fatigue strength of built-up roofing membranes tested at 73 °F.*

the punching shear strength of the membranes placed over the five types of insulation.

Three different diameter steel probes were used in the tests. The diameters were ½, ¾, and 1 in. The test specimen (membrane over insulation) was placed over a simulated steel deck so that the 8 × 12 inch specimen spanned a 2⅜-inch flute opening. The force was applied at midspan of the unsupported length of the specimen. Data from the ¾-in probe tests are shown in figure 4. Results of the tests at 0 °F gave, in general, high shear strengths and smaller corresponding indentation depth.

Tests using the ½-in diam probe gave more scatter and range of data than when the ¾ in diam probe was used. The 1-in diam probe gave data which was more uniform with very little scatter and range compared to data from the ¾ in probe tests.

5.1.7. Impact Resistance

Five types of four-ply, built-up roof membranes placed over five types of insulation were tested to determine their resistance to impact. Ice spheres, simulated hailstones, were impacted on the face of the test specimens to simulate hail. The diameter of the ice spheres used in the tests were 1, 1¼, 1½, 1¾, 2, and 2½ in. The speed of the ice spheres corresponded to the speed at which hailstones hit the ground. It was found, in general, that 1½-in diam ice spheres traveling at 112 feet per second (ft/s) did not damage the membranes. Damage was observed in the membranes when larger size ice spheres were used.

5.2. Planned Performance Tests

It is planned to carry out the development of performance tests for the attributes listed in section 4 for which tests are not available. Upon completion of these additional tests, the performance criteria in section 6 will be expanded to include the results of the needed laboratory studies. It is expected that as information is developed relating to performance of built-up roofing, the levels of performance will also be revised and updated.

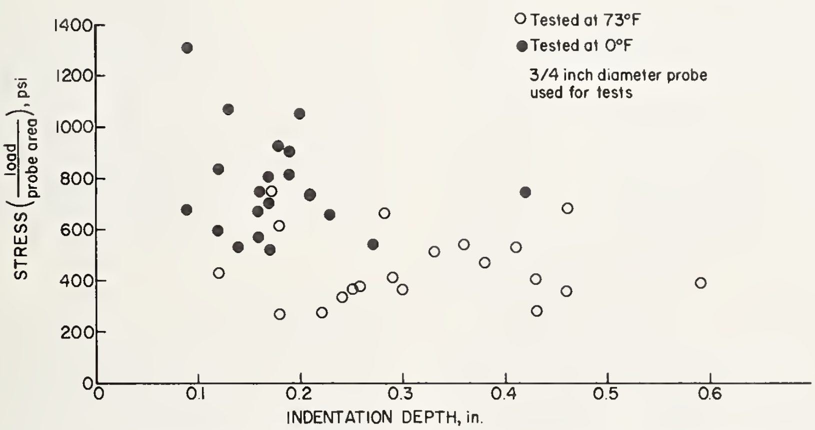

FIGURE 4. *Punching shear strength of built-up roof membranes and corresponding indentation depth.*

6. Recommended Performance Criteria

The recommended performance criteria are considered preliminary and will be revised or updated when additional information becomes available. Obviously, some of the performance tests and corresponding criteria may not be needed and may be deleted after reviewing the completed performance criteria. As an example, both the tensile strength and flexural strength may not be needed in the criteria. Since both are essentially related to the membranes tensile strength properties. Experience may prove that both impact resistance and shear strength can be combined into one criterion.

Based on research conducted in this program, as well as research conducted concurrently in other investigations and previously at the National Bureau of Standards and elsewhere, it is possible, even at this early stage, to state examples of criteria for roofing membranes. In order to place the performance concept as it applies to roofing in perspective, the authors felt it would be useful to incorporate known data into the performance format. As a point of departure, several examples are given. The values are preliminary and should not be construed to be final values. As results are obtained from performance in-service experience and laboratory research, the values will continue to be updated and adjusted to reflect the developing state-of-the-art.

6.1. Performance Format

6.1.1. Tensile Strength

Requirement The roof membrane shall withstand, without rupture, the normal stresses imposed from internal or external causes.

Criterion The tensile strength shall not be less than *200 lb/in* in the weakest direction of the membrane when tested at 0 °F.

Test ASTM D–2523 testing load-strain properties of roof membranes.

Commentary This criterion is based on performance in service. Certain membranes exhibit anisotropic behavior. Therefore, the results of tests in the weakest direction (usually transverse or "cross machine" direction) should apply.

6.1.2. Thermal Expansion

Requirement The roofing membrane shall not exhibit large movements when subjected to temperature change.

Criterion The linear expansion coefficient shall not exceed $40 \times 10^{-6}/°F$.

Test NBS test procedures (ASTM Proposed Method of Test for "Coefficient of Linear Thermal Expansion of Roofing and Waterproofing Membranes," ASTM Annual Book of Standards, Volumn 15, 1974). Coefficient to be determined from temperature range 0 to −30 °F.

Commentary Most roof membranes exhibit anisotropic properties regarding temperature change. Test should usually be performed in the transverse or "cross machine" direction since greater movement is generally expected in this direction. Areas which are not subject to cold weather may establish larger limits for the coefficient of linear expansion.

6.1.3. Thermal Movement

Requirement The roof membrane shall withstand the normal temperature changes of its environment.

Criterion The thermal shock resistance factor should not be less than *100 °F*.

Test NBS test procedures as described in this paper.

Commentary Areas which are not subject to large and sudden temperature changes may establish lower limits for the thermal shock resistance factor.

6.1.4. Flexural Strength

Requirement The roof membrane shall withstand, without rupture, the normal bending stresses imposed from external causes.

Criterion The load capacity in flexure for a one-inch wide strip with fixed ends and loaded at midspan (7-in span) at 0 °F should be at least *30 lb*.

Test NBS test described in this paper.

Commentary Certain membranes exhibit anisotropic behavior, the results of the tests in the weakest direction (usually transverse or "cross machine") should apply.

6.1.5. Tensile Fatigue Strength

Requirement The roof membrane shall withstand, without rupture, repeated forces causing high and low levels of tensile stress in the membrane.

Criterion The roof membrane shall withstand without rupture a minimum of *100,000 cycles* of repeated force (tension) of 20 lb when tested at 73 °F and a minimum of *100,000 cycles* of repeated force (tension) of 100 lb when tested at 0 °F.

Test NBS test described in this paper.

Commentary Certain membranes exhibit anisotropic behavior, the results of the tests in the weakest direction (usually transverse or "cross machine") should apply.

6.1.6. Flexural Fatigue Strength

Requirement The roof membrane shall withstand, without rupture, repeated forces causing high and low levels of bending stress in the membrane.

Criterion The roof membrane shall withstand without rupture a minimum of *10,000 cycles* of force causing a deflection of *0.125 in* at midspan (7-in span) of a one inch wide strip with fixed ends tested at 73 °F.

Test NBS test described in this paper.

Commentary Certain membranes exhibit anisotropic behavior, the results of the tests in the weakest direction (usually transverse or "cross machine") should apply.

6.1.7. Punching Shear Strength

Requirement The membrane shall withstand, without rupture, vertical punching shear forces from foot traffic and other effects.

Criterion The punching shear strength shall not be less than *250 psi* (force/probe area), when tested at 73 °F using a ¾-in diam probe.

Test NBS test described in this paper.

Commentary Membrane should be attached to the insulation when conducting the test.

6.1.8. Impact Resistance

Requirement The roof membrane should withstand the impact from hailstones and other falling objects.

Criterion The roofing membrane should be able to withstand an impact of a *1 1/2-in* diam hailstone falling at a speed of *112 ft/s* without allowing penetration of water.

Test NBS Hail Resistance Test, Building Science Series No. 23.

Commentary The test does not approximate the energy of large sharp objects, as large icicles or tree limbs. Areas which are not subject to hailstorm or falling icicles could establish lower limits for impact resistance.

6.1.9. Wind Resistance

Requirement The roof membrane shall withstand anticipated wind loads without damage.

Criterion The roof membrane should meet the requirements of class (*30*), (*60*), or (*90*) according to Underwriters' Laboratory Bulletin of Research No. 54. Note, one class should be selected depending on local wind conditions.

Test Underwriters' Laboratories test procedure described in UL Bulletin of Research No. 54, 1962.

Commentary The above criterion is believed adequate for most locations in the United States. However, in high wind areas, a more rigid criterion may be needed. Other tests such as those recommended by Factory mutual and Owens-Corning Fiberglas Corporation may be suitable.

6.1.10. Fire Resistance

Requirement The roofing membrane should not be susceptible to ignition from sparks and fire brands.

Criterion The intermittent flame, flame spread and burning brand rating of the membrane should be classified according to Underwriters' Laboratory Bulletin UL–790 as (*A*), (*B*), or (*C*) as required by local codes.

Test ASTM E–108. Underwriters' Laboratory Bulletin, UL–790 describes test procedure and rating values.

Commentary The ASTM test method with limits established by UL criterion are believed adequate for most locations in the United States. This criterion has been widely used by the roofing industry and has gained acceptance.

7. Summary and Conclusions

The major goal of the research was to develop performance criteria which would contain quantitative definitions of the roof membranes overall performance under service conditions. Preliminary performance criteria were recommended along with tests to measure performance of roof membranes for nine of the 20 attributes that were identified. These attributes have a significant impact on the total performance of membrane roofing. The values given are based on data obtained from the four, and in some cases, five types of basic four ply membrane specimens. From the authors experience, it is believed that four ply membranes constructed in a similar fashion as those described in this paper and properly applied would perform adequately in any area of the United States provided they comply with the stated performance criteria in section 6. However, established performance criteria would not require membranes to have a specific number of plies.

The laboratory program was intended to develop tests which are needed to measure performance of roof membranes. Some of the tests described are new, other are modifications of existing tests and some are established tests which have satisfactorily served the roofing industry in the past. The new tests include flexural strength, tensile fatigue strength, flexural fatigue strength, punching shear strength and impact resistance. The tests that were modified include tensile strength, thermal expansion and thermal movement. Tests that were not changed are those used by the roofing industry for wind resistance and fire resistance.

Laboratory tests which need to be developed to complete the performance criteria include notch tensile strength, moisture effects on strength, creep, ply adhesion, abrasion resistance, tear resistance, pliability, permeability, moisture expansion, weather resistance, and fungus attack resistance. Research is being continued in some of these areas.

As performance criteria for membrane roofing become more complete, it is expected that some of the performance characteristics can be deleted or combined with others to reflect the current state-of-the-art. It is also anticipated that additional performance attributes may be needed and described quantitatively to make the performance criteria more meaningful. Such needs should be studied carefully with respect to one, two or three ply systems.

With the establishment of acceptable performance criteria for membrane roofing at least two benefits are readily apparent. First, the criteria would provide the basis for the evaluation of both presently used roofing systems and innovative membranes with regard to expected in-service performance. Secondly, they can be used by manufacturers as a guide in the production of roofing materials and, in particular, the development of new products for membrane roofing. In addition to these two benefits, performance criteria will enhance better and more economical service from bituminous membranes. The development of adequate criteria for membrane roofing based on quantitative terms will provide an important step in elevating the art of roofing to some resemblance of a science.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report is the first in a series of publications on performance criteria for built-up roof membranes. The development of a performance approach to bituminous built-up roof membranes is described and preliminary performance criteria are recommended. A number of test methods have been developed in order to obtain data to evaluate roofing membranes against the recommended criteria. Twenty attributes that effect the performance of roof membranes under service conditions are identified and laboratory tests are described for measuring the engineering properties of the membrane that pertain to many of these attributes. A level of performance is recommended for nine of the identified performance attributes.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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