STRAIN ENERGY OF BITUMINOUS BUILT-UP MEMBRANES: A NEW CONCEPT IN LOAD-ELONGATION TESTING

WALTER J. ROSSITER, JR. and DALE P. BENTZ

National Bureau of Standards
Gaithersburg, Md.

This study was conducted to revise the performance criterion for tensile strength of bituminous built-up membranes. Bituminous membrane samples, fabricated from polyester fabric, polyester-glass composite fabric, and single plies of APP- and SBS-modified bitumen, were tested in tension to determine their load-elongation properties and to measure their strain energy. The results of the tensile tests of the new bituminous membranes indicated wide variability of load and elongation among the different types of materials. As an alternative to the criterion that a bituminous built-up membrane have a tensile strength of 200 lbf/in (35 kN/m), it was recommended that the strain energy should be a minimum of 3 lbf•in/in (13 N•m/m), when tested at 0°F (−18°C) in the weaker direction.

Key words: bituminous roofing; built-up; low-sloped; performance criterion; polyester; polymer-modified bitumen; roofs; strain energy; tensile strength.

BITUMINOUS BUILT-UP ROOFING

Bituminous built-up membranes have been used for over a century to provide the waterproofing element in low-sloped roofing systems for industrial and commercial buildings. Until the mid-1970's, almost all low-sloped roofing systems in the United States were the bituminous built-up type. Although since that time built-up membrane applications have declined, recent estimates indicate that in 1985 bituminous built-up membranes accounted for about 50 percent of those installed.[1]

Over the years, the majority of bituminous built-up membranes have performed satisfactorily, but nevertheless, premature failures have often occurred.[2] Since the early 1970's a number of steps have been taken by the industry to help assure the satisfactory performance of built-up roofing including:

- increasing the awareness of owners, manufacturers, and contractors of the need for proper specifications, and for quality installation and maintenance,[3-5]
- the development of preliminary performance criteria,[6]
- an increase in laboratory and field research to provide the basis for standards and solutions to problems,[7] and
- changes in the types of reinforcements used in built-up membrane fabrication.[8]

The change in the types of reinforcements, as well as bituminous materials, has been drastic.[8,9] For example, glass mats now command the major share of the felt reinforcement market, and materials such as polymer-modified bitumens and polyester fabrics are readily available. The introduction of new types of reinforcements for built-up roofing has resulted in a need to reexamine and possibly modify existing performance criteria for bituminous membranes.[10,11] This present report presents a summary of a study to revise the performance criterion regarding tensile strength. A strain energy criterion is suggested as a complement to the tensile strength criterion. A detailed report of the study has been previously published.[12]

PERFORMANCE CRITERIA AND SPLITTING

In 1974, Mathey and Cullen reported on preliminary performance criteria for bituminous membrane roofing.[6] They identified 20 performance attributes for these membranes, and suggested preliminary criteria for 10 of the attributes. The 20 attributes were selected upon consideration of the membrane characteristics necessary to resist development of typical defects and premature failure in service. Splitting, which is tearing of the membrane resulting from tensile stress,[3] is one of the most commonly occurring defects.[1,14,15] As is obvious, it has disastrous consequences, since the waterproofing integrity of the membrane is lost.

Of the preliminary performance criteria suggested by Mathey and Cullen, the tensile strength criterion is considered important to the ability of the built-up membrane to resist stresses imposed in service.[11] The performance criterion for tensile strength is that the membrane should have a minimum strength of 200 lbf/in (35 kN/m), when tested at 0°F (−18°C) in the weakest direction of the membrane.[6] The development of this criterion was based on the load-elongation properties of bituminous built-up membranes available at the time and their performance in service. For example, when tested as described in the tensile strength criterion, many traditional built-up membranes had tensile strengths greater than 200 lbf/in (35 kN/m) and elongations at break in the range of 1–3 percent. However, some of the new (or non-conventional) membranes fabricated from synthetic reinforcements such as polyester fabrics or from polymer-modified bitumens have tensile strengths less than 200 lbf/in (35 kN/m) and elongations at break of 20 percent or more. For the limited time in service, the performance of many of these non-conventional materials has been satisfactory.[16-18] Concerns that they may be prone to splitting have not been reported, suggesting that the performance criterion of 200 lbf/in (35 kN/m) is not a requisite for acceptable performance of bituminous built-up membranes in cases where they are relatively extensible (e.g., having an extensibility greater than 1–3 percent).

STRAIN ENERGY

A preliminary study[11] was conducted at the National Bureau of Standards (NBS) to propose possible alternative approaches that might be taken to revise the tensile strength criterion. The study suggested that a strain energy approach be used. Strain energy is the energy that a material absorbs as a result of its deformation,[19] and is measured as the area under the load-deformation curve (Fig. 1). An important advantage in selecting the strain energy approach was that it was compatible with the original tensile strength criterion in that tensile strength and strain energy are properties measured in the same tensile test.

The area under the entire load-deformation curve is a measure of the strain energy required to rupture a material.[19] It is related to toughness, which represents a material's ability to resist energy loads before rupture. Traditional built-up membranes may be considered as having relatively high strength and low deformation, while some of the non-conventional membrane materials may have relatively low strength and high deformation (Fig. 1). As is evident from Fig. 1, a high strength material having low capacity to deform may have less toughness than a low strength material having high capacity to deform. When in place on a given building, a non-conventional membrane material would be exposed to the same environmental conditions (which can produce splitting forces) as experienced by a traditional bituminous built-up membrane. Thus, as a measure of splitting resistance that includes both strength and extensibility of the membrane, it is considered that the non-conventional membrane materials should have strain energies at least comparable to those of the traditional bituminous built-up membranes that have historically provided acceptable long-term performance.

The use of strain energy as a criterion must also include a consideration of the watertightness of the membrane upon elongation. Some of the non-conventional bituminous built-up membranes, having greater elongation at break than the traditional ones,[16] may not remain watertight when elongated at low temperatures to values approaching ultimate.

The application of strain energy in the specification of bituminous built-up membranes having varying load-deformation properties is not a new concept.[11] The Canadian General Standards Board (CGSB) Standard[20] and the Midwest Roofing Contractors Association (MRCA) Performance Criteria[21] for polymer-modified bitumens both have requirements for minimum strain energy for these materials. However, these two documents refer to strain energy at break and do not consider the watertightness of the membrane after some limited elongation which does not reach the break point.

EXPERIMENTAL

Complete experimental details have been previously given.[12] A summary is given in the present report.

Membrane samples

Commercially available, bituminous membrane samples (1–9) were used for the determination of the strain energy criterion and are described in Table 1. The orientations of the test specimens, relative to the direction of the manufactured roll of reinforcing fabric, were longitudinal (machine-direction), transverse (cross-machine direction), and diagonal (45° to the machine direction).

Four other polyester-based built-up membrane samples (10–13) were prepared using asphaltic emulsion and tested in tension for comparison of their strain energy with that suggested in the revised criterion. These samples are described in Table 2.

Tensile test

All samples were tested in tension using a universal testing machine at a rate of 0.08 in/min (2mm/min). The machine was equipped with a microcomputer for data acquisition, reduction, and storage, as well as for calculating the strain energy of the specimens. Tests were carried out at 73, 0, and −30°F (23, −18, and −34°C). The test-specimen configuration was as described in ASTM D2523. Five specimens of each membrane sample were tested at each temperature for each orientation. The strain energy was calculated on the basis of unit gauge length.

Watertightness test

Watertightness tests were conducted according to the procedure given in the Canadian General Standards Board (CGSB) Standard for polymer-modified bitumens.[20] Before conducting the watertightness tests, the specimens were elongated to the minimum strain energy suggested in the revised performance criterion (see below.

RESULTS

When tested in tension, the nine membrane samples described in Table 1 showed, as expected, varying load-elongation properties. This is illustrated in Fig. 2, which presents the results of the tests at 0°F (−18°C) for specimens tested in the transverse direction. Several samples (1–4, and 8) exhibited relatively high peak loads that occurred at break with relatively little elongation. Peak load is defined as the maximum load recorded during the tension test. One sample (9) gave a peak load during the initial portion of the test (due to break of the reinforcement), and had a relatively high elongation at break. For another sample (7), the peak load occurred essentially at break with relatively high elongation. Two samples (5 and 6) exhibited low load and intermediate elongation.

Tables 3, 4, and 5 present summaries of the average tensile strength, percent elongation, and calculated strain energy for the tension tests. Tensile strength is given as the peak load experienced during testing. Depending on the sample, the peak load occurred at the initial stages of elongation or at the ultimate elongation. For those cases where the peak load occurred during initial specimen elongation, the percent elongation and strain energy are given for peak loads and also for the break point of the specimens (referred to in the tables as ultimate elongation and total strain energy, respectively). When the peak load occurred at specimen break, only values of ultimate elongation and total strain energy are reported (Tables 4 and 5). In some tests, a rapid, large loss of load occurred just prior to specimen break (for example, Fig. 3, specimen 7). In these cases also, only the ultimate elongation and total strain energy are reported.

DISCUSSION

Conventional built-up membranes

Conventional four-ply bituminous built-up membranes using organic and glass felts (samples 1 and 2, respectively) were included in the study to compare their load-elongation properties at 0°F (−18°C) with those of the non-conventional membrane materials. The strain energies at 0°F (−18°C) for the four-ply organic and glass built-up membranes were 3.2 and 4.0 lbf•in/in (14.0 and 17.6 N•m/m), respectively. The greater value of strain energy for the glass felt membrane was attributed, for the most part, to its greater tensile strength (Table 3). The ultimate elongations for the two conventional membrane samples were found to be similar (Table 4). The values of tensile strength of both the organic and glass felt membrane samples (Table 3) were similar to those reported by Mathey and Cullen[6] for these types of materials.

Non-conventional bituminous membrane materials

Little data on the load-elongation properties of polyester-reinforced bituminous built-up membranes have been reported for different test temperatures and orientations of fabric in the membrane specimen.[16] Thus, for purposes of characterization, three-ply specimens of polyester-based bituminous built-up membranes (samples 3–7), oriented in the longitudinal, transverse, and diagonal directions of the fabric, were tested in tension at 73, 0, and −30°F (23, −18, and −34°C).

Tensile properties for the diagonal direction of conventional membrane materials are normally not measured. In this study, the tensile properties of the non-conventional membrane materials were determined for the diagonal direction, since some of these materials contained reinforcement which could contribute to strength of the fabric in the longitudinal and transverse directions, but might have little influence on strength in the diagonal direction. For such materials, the diagonal direction of the fabric would then be the weakest orientation.

The results of the study showed that the polyester fabrics having the bonded glass net (samples 3 and 4) were weakest in the diagonal direction (Table 3). However, this finding should, in general, have little impact on the use of the glass-reinforced polyester fabrics for built-up membranes, since in normal practice, the fabric orientation during application would be perpendicular to the long joints between insulation boards. Thus, further discussion of the data regarding the orientation of the fabric in the test specimens will be limited to the longitudinal and transverse directions.

The APP (atactic polypropylene)- and SBS (styrene-butadiene-styrene)-modified bitumens were included in the test program to compare the load-elongation properties of typical polymer-modified bitumens to those of bituminous built-up membrane materials. In developing the scope of the study, it was intended to explore whether the revised performance criterion for tensile strength would have applicability to typical polymer-modified bitumens.

Tensile strength With one exception, the membrane samples were weaker in the transverse direction than the longitudinal direction at each of the test temperatures (Table 3). One polyester sample (7) was weaker in the longitudinal direction. The method of manufacture for this polyester fabric was different than that used for the other two polyesters (sample 5 and 6).

For a given orientation (e.g., transverse), all membrane samples were weakest at 73 °F (23 °C) (Table 3). At the lower test temperatures, the strength of the samples increased. The maximum tensile strength was found at either 0 or −30°F (−18 or −34°C) depending upon the membrane material (Table 3).

The load-elongation behavior of three samples (3, 4, and 8) for the transverse direction at 0°F (−18°C) was similar to that of the conventional built-up membranes (1 and 2), as illustrated in Fig. 3. The strength of samples 3 and 4 at 0°F (−18°C) was attributed to the glass net bonded to the polyester fabric. Peak load was achieved when the glass net failed. The polyester fabric did not break at this point. However, delamination of the three plies of polyester fabric in the specimens occurred simultaneously with the glass-net rupture. Because of the delamination, the membrane specimens were considered failed, and the tension test was terminated.

Percent elongation For all orientations at 73°F (23°C), the non-conventional bituminous membrane materials had, with one exception, ultimate elongations ranging from approximately 15 to 150 percent (Table 4). These values were substantially greater than the ultimate elongations of conventional built-up membranes, which may range from about 1 to 4 percent* at ambient temperatures. The ultimate elongation of sample 8 was only slightly greater than 1 percent at 73°F (23°C).

As the temperature was decreased below 73°F (23°C), the ultimate elongations of all samples except 8 decreased. In general, sample 8 exhibited little change in percent elongation over the range of test temperatures (Table 4).

Three of the polyester-based samples (3, 4, and 7) had comparable elongations at 0 and −30°F (−18 and −34°C) for a given orientation. Polyester sample 5 had its lowest percent elongation (for all orientations) at 0°F (−18°C). The percent elongation was twice as great at −30°F (−34°C) as at 0°F (−18°C), as shown in Fig. 4, which gives load-elongation curves in the transverse direction at the three test temperatures.

Strain energy The total strain energies of the non-conventional membrane materials varied considerably between some samples, which reflected the differences in their peak loads and ultimate elongations (Table 5). For the longitudinal and transverse directions, four polyester-based samples (3–6) were found to have their greatest total strain energy at 73°F (23°C), which was attributed to their relatively high elongations at this temperature. For these four samples, as the test temperature decreased below ambient, the total strain energy decreased. The minimum strain energy was found at either 0 or −30°F (−18 or −34°C) depending on the load and elongation of the membrane material. For example, it is evident from Fig. 4 that, for three test temperatures, the total strain energy of sample 5 was least at 0°F (−18°C), which was primarily attributed to the lower elongation at this temperature.

For a given orientation, the total strain energies of polyester sample 7 were comparable at the three test temperatures. In this case, relative increases in load and decreases in ultimate elongation, as the temperature was reduced below 73°F (23°C), produced little effect on the strain energy (Fig. 5). In the case of both polymer-modified bitumens (samples 8 and 9), the relative changes which occurred in load and ultimate elongation, as the test temperature was decreased, resulted in the samples having their greatest total strain energy at 0°F (−18°C) (Table 5).

At 0°F (−18 °C) for the weaker membrane direction, two of the five polyester-based samples (3 and 7) had a total strain energy greater than that of the four-ply organic membrane sample (1) (Table 5). In contrast, for the same conditions, the other three polyester-based samples (4, 5, and 6) had a total strain energy less than that of the organic membrane sample. Fig. 6 compares typical load-elongation curves for the polyester samples (5, 6, and 7) with a curve for the organic membrane sample (1).

REVISED PERFORMANCE CRITERION FOR TENSILE STRENGTH

The approach taken for revising the tensile strength performance criterion is to use the strain energy of the membrane as an alternative to tensile strength. A major difficulty in suggesting the use of strain energy is the selection of a minimum value which the membrane material should possess under the given test conditions. As a first step to resolve this difficulty, it is considered that the minimum value of strain energy should be based on the strain energy of built-up membrane materials which have provided acceptable performance. In this regard, four-ply organic built-up membranes, properly applied and maintained, have, in general, performed satisfactorily for many years.[6,24] Until recent times, membranes having organic felts were the most commonly used, and provided an industry benchmark against which the performance of other types of membrane materials was compared. For this reason, it is suggested that a minimum value of strain energy (for use as a performance criterion) be comparable to that of typical four-ply organic bituminous built-up membranes. It is noted that four-ply organic membranes generally have shown conformance to the tensile strength criterion of 200 lbf/in (35 kN/m).

Although four-ply organic built-up membranes having different brand names are generically the same type of material, they do not

*Unpublished NBS data.

all have equivalent strain energies. This is due, in part, to differences in load-elongation properties imparted to the felts during the manufacturing process. Table 6 compares the tensile strength, ultimate elongation, and strain energy of some typical four-ply organic membranes. With the exception of the sample tested in the present study, the strain energy of the other samples was estimated from load-elongation data given in the referenced papers.[6,23,25] Strain-energy data were not presented in these references. Table 6 indicates that the strain energy of the samples was in general estimated to be about 3 lbf.in/in (13 N•m/m) or greater. In one case of a coal tar pitch membrane, the estimated strain energy was 1.7 lbf•in/in (7.6 N•m/m), which was attributed to the low elongation (0.9 percent) of the sample.

Based on the limited data given in Table 6, it is suggested that a preliminary minimum value of strain energy of 3 lbf•in/in (13 N•m/m) be used in the revision of the performance criterion for tensile strength. Additional data from load-elongation tests of four-ply organic built-up membranes, or others, may result in a value of strain energy superseding the presently suggested value.

The revised performance criterion for tensile strength is presented in Table 7. As previously discussed, a watertightness test must be conducted on membrane materials which conform to the strain energy portion of the criterion. The watertightness test should be conducted on the specimen after it is elongated at 0°F (−18°C) to a percent at which the strain energy is equivalent to the criterion value of 3 lbf•in/in (13 N•m/m). If the specimen is not watertight after that elongation, it is considered to be non-functional, and would not meet the criterion.

The watertightness test in the CGSB Standard for polymer-modified bitumens[20] was used in the present study to demonstrate watertightness of the elongated membrane specimens. The test was selected because it was available in a national standard developed in North America. The description of the procedure in the standard indicated that the test should be easily conducted in the laboratory. However, difficulty was encountered in sealing membrane test specimens to the vertical tubes containing the columns of water that provided pressure for the tightness test. Hot wax was found to provide the best seals, but sealing was still difficult to accomplish. The test was considered adequate for purposes of demonstrating watertightness in this study. Because of the difficulties encountered in the present study, it is suggested that, for future application of the tensile strength criterion, another watertightness test should be used or an improved test procedure be developed.*

Comparison of test samples to the revised criterion

Table 8 compares the bituminous membrane materials included in the study with the revised performance criterion for tensile strength. Five samples (1–4, and 8) showed conformance to the original criterion of having a tensile strength of 200 lbf/in (35 kN/m). Watertightness tests were not conducted on these samples, since loss of watertightness of built-up membranes (which have relatively low extensibility) during elongation to break has never been of concern. These materials provide waterproofing capability as long as they do not split, puncture, or incur similar damage.

*During the course of the study, conversations were held with Dr. R. Booth, present chairman of the CGSB task group having responsibility for the standard. He indicated that the standard is being reviewed for possible revision. One concern being addressed is the significance of the current test procedure for demonstrating watertightness of a damaged membrane specimen.

Sample 7 and 9 did not conform to the tensile strength criterion, but did meet the strain energy criterion of 3 lbf•in/in (13 N•m/m). These samples were also watertight when tested according to the procedure in the CGSB Standard. Prior to the watertightness test, sample 7 was elongated 5 percent at 0°F (−18°C). Sample no. 9 was elongated to 3.5 percent. At these elongations, the strain energy of the specimens was about 3•lbf•in/in (13 N•m/m).

Two polyester samples (4 and 5) did not show conformance to either the tensile strength or strain energy criterion. The two polymer-modified membrane materials met the revised performance criterion. The APP-modified bitumen (8) showed conformance to both the tensile strength and strain energy portions of the criterion. The SBS-modified bitumen (9) was in conformance with the strain energy section.

Finally, it is noted that the tests of the bituminous built-up membranes were conducted only on new samples prepared in the laboratory. The test specimens were not subjected to any exposure conditions, either in the laboratory or outdoors, which might be considered deleterious to the membranes. The minimum strain energy of 3 lbf•in/in (13 N•m/m) should be maintained by a membrane as it ages. Changes in membrane properties that occur due to weathering and diurnal cycling should not result in a strain energy less than the suggested minimum. Further research is needed to investigate whether the non-conventional bituminous built-up membranes maintain an acceptable minimum value of strain energy after performance in service.

Comparison of additional samples to the revised criterion

Laboratory samples Table 9 presents the tensile strength, ultimate elongation, and total strain energy for the additional polyester-based membrane samples (10–13). As previously indicated, these samples were tested for comparison of their strain energy with that suggested for the revised performance criterion. Three replicate specimens of each sample were tested at 0°F (−18°C) in the transverse direction of the fabric. As is evident in Table 9, the total strain energies of the four specimens were found to be greater than the suggested criterion value of 3 lbf•in/in (13 N•m/m). Watertightness tests were not conducted on the four specimens. To determine total conformance to the revised criterion, a watertightness test of the samples would need to be conducted.

In conducting the additional tests, it was of interest to investigate whether a surface coating of asphaltic emulsion would influence the polyester sample tensile strength. Sample 10 and 11 were prepared from the same fabric and were identical except that one outer surface of 10 was coated, whereas the two surfaces of 11 were coated (Table 9). Samples 12 and 13 also formed an identical pair except for surface coating. Strict comparison of the effect of the surface coating is difficult to make because of the limited number of replicate specimens tested. As given in Table 9, the former pair (10 and 11), had comparable tensile strengths, whereas the latter pair (12 and 13) had tensile strengths differing by about 25 percent. Visual examination of the test specimens seemed to indicate that the asphaltic emulsion penetrated the polyester fabric used for samples 12 and 13 more than it penetrated the fabric used to prepare samples 10 and 11. The penetration of the asphaltic emulsion into the fabric could provide increased fabric strength.

Field samples Determination of the load-elongation properties of polyester-based built-up membranes removed from roofs after some period of service was beyond the scope of the present study.

Limited data[26] are available in the U.S. from Dupuis* and are summarized in Table 10. Two of the field samples had two plies of polyester reinforcement. The ages of the two-ply samples were two and 0.5 years. A third field sample consisted of one ply of Type IV glass and two plies of polyester reinforcement, and had an age of 0.5 years. The data in Table 10 may be compared with the revised load-elongation performance criterion. The three field samples had load-elongation properties, as determined as 0°F (−18°C) by Dupuis,[26] in accordance with the revised criterion. From Table 10, it is evident that the total strain energy of the field samples was greater than 3 lbf•in/in (13 N m/m), and the three samples were watertight when tested after elongation to a percent equivalent to 3 lbf•in/in (13 N•m/m) strain energy. For the watertightness test, a 6-inch (150mm) head of water was used, and not the 20-inch (500mm) water head as described in the present paper.

RECOMMENDATIONS

This study was conducted to revise the performance criterion for tensile strength of bituminous built-up membranes. This criterion is that the tensile strength of the membrane should be a minimum of 200 lbf/in (35 kN/m), when tested in the weaker direction at 0°F (−18°C).[6] A strain energy approach was taken to revise the tensile strength criterion. A strain energy criterion considers both the strength and extensibility of the membrane, and is related to the toughness of the material to withstand energy loads before rupture. As an alternative to the criterion that a bituminous built-up membrane has a tensile strength of 200 lbf/in (35 kN/m), it is recommended that the strain energy should be a minimum of 3 lb•in/in (13 N•m/m), when tested at 0°F (−18°C) in the weaker direction. This value of strain energy was selected based on a summary of limited load-elongation data for conventional four-ply organic bituminous built-up membranes.

When strain energy is used as a criterion, it is necessary to conduct a watertightness test to assure that limited strain of the membrane at low temperatures does not occur to an extent that cracks the bitumen, resulting in loss of waterproofing integrity. It is recommended that a watertightness test be conducted on specimens after partial elongation to a percent corresponding to the minimum strain energy of 3 lfb•in/in (13 N•m/m).

The data on which the strain energy criterion was developed were obtained from tests of new laboratory-prepared specimens. A membrane should maintain a strain energy above the suggested minimum throughout its service life. Further research is needed to investigate whether the non-conventional bituminous built-up membranes maintain an acceptable minimum value of strain energy after long-term in-service performance.

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*Personal communication, R.M. Dupuis, Structural Research Inc.

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Sample No.	Plies No.	Membrane reinforcement[a]	Interply bitumen[b]
1	4	Organic felt	Asphalt
2	4	glass felt	Asphalt
3	3	Polyester/glass fabric[c,d] (2 ounce/square yard)	Asphalt
4	3	Polyester/glass fabric[e] (2 ounce/square yard)	Asphalt
5	3	Polyester fabric (2 ounce/square yard)	Asphaltic emulsion
6	3	Polyester fabric (2 ounce/square yard)	Asphaltic emulsion
7	3	Polyester fabric (3 ounce/square yard)	Asphaltic emulsion
8	1	AAP-Modified bitumen[f]	None
9	1	SBS-Modified bitumen[g]	None

a. The organic felt was ASTM D 226, Type I; the glass felt was ASTM D 2178, Type IV; there were no ASTM standards available for the polyester or polymer modified bitumen materials.

b. The asphalt was ASTM D312, Type III; the asphaltic emulsion did not conform to an ASTM standard.

c. This material was a composite of a filament glass net (five strands) to the inch) bonded between two layers of polyester fabric.

d. The parenthetical expression is a fabric descriptor. The textile industry describes fabrics by mass per unit area, normally ounces per square yard or grams per square meter.

e. This material was a composite of a filament glass net (six strands to the inch) bonded on one surface of a polyester fabric.

f. AAP indicates that the modifier was atactic polypropylene.

g. SBS indicates that the modifier was styrene-butadiene-styrene.

Table 1 *Membrane materials used for test specimens for determination of the strain energy criterion*

Sample No.	Plies No.	Membrane reinforcement[a]	Interply bitumen[b]	Surface coating[c]
10	3	Polyester fabric (3 ounces/sq yard)[d]	Asphaltic emulsion	1 side
11	3	Polyester fabric (3 ounces/sq yard)	Asphaltic emulsion	2 sides
12	3	Polyester fabric (3 ounces/sq yard)	Asphaltic emulsion	1 side
13	3	Polyester fabric (3 ounces/sq yard)	Asphaltic emulsion	2 sides

a. There were no ASTM standards available for the polyester fabric materials.

b. The asphaltic emulsion did not conform to an ASTM standard.

c. Emulsion was applied to one or both outer surfaces of the test specimens in addition to the interply application.

d. The parenthetical expression is a fabric descriptor. The textile industry describes fabrics by mass per unit area, normally ounces per square yard or grams per square meter.

Table 2 *Membrane materials used for samples tested in comparison to the strain energy criterion*

Sample no.	73°F (23°C)			0°F (−18°C)			−30°F (−34°C)		
	Peak load[b]			Peak load[b]			Peak load[b]		
	L[c]	T[d]	D[e]	L[c]	T[d]	D[e]	L[c]	T[d]	D[e]
1					287 (50.3)				
2					370 (64.8)				
3	211 (36.9)	154 (27.0)	79.0 (13.8)	342 (59.8)	288 (50.5)	144 (25.3)	392 (68.7)	317 (55.6)	113 (19.8)
4	170 (29.7)	147 (25.7)	68.5 (12.0)	279 (48.9)	202 (35.4)	92.5 (16.2)	315 (55.2)	235 (41.2)	72.2 (12.7)
5	43.6 (7.6)	33.1 (5.8)	40.7 (7.1)	55.9 (9.8)	44.9 (7.9)	53.7 (9.4)	45.1 (7.9)	33.8 (5.9)	41.1 (7.2)
6	74.5 (13.0)	26.3 (4.6)	38.6 (6.8)	105 (18.5)	32.9 (5.8)	51.7[f] (9.1)	99.0 (17.3)	29.1 (5.1)	44.3 (7.8)
7	62.6 (11.0)	90.7 (15.9)	67.0 (11.7)	101 (17.7)	168 (23.4)	106[f] (18.6)	95.6 (16.7)	130 (22.7)	107 (18.7)
8	125 (21.9)	93.5 (16.4)	89.6 (15.7)	289 (50.6)	251 (44.0)	265 (46.5)	195 (34.1)	152 (26.5)	167 (29.3)
9	94.3 (16.5)	55.4 (9.7)	72.2 (12.6)	217 (38.1)	144 (25.2)	156 (27.3)	295 (51.6)	204 (35.6)	219 (38.3)

a. Data on the coefficients of variation have been previously given.[12]

b. Unless otherwise indicated, average of five tests.

c. Longitudinal direction.

d. Transverse direction.

e. Diagonal direction.

f. Average of four tests.

***Table 3** Tensile strength of membrane samples used in the determination of the revised criterion, lbf/in. (kN/m)[a]*

Sample no.	73°F (23°C)						0°F (−18°C)						−30°F (−34°C)					
	At peak load			At ultimate elongation			At peak load			At ultimate elongation			At peak load			At ultimate elongation		
	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]	L[b]	T[d]	D[d]	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]
1								—[e]			1.5							
2								—			1.7							
3	3.3	2.4	34.2	22.9	15.6	40.5	—	—	4.3	2.3	1.8	8.5	—	—	2.3	3.0	2.0	5.9
4	2.3	2.9	30.8	19.4	23.1	35.8	—	—	4.5	1.8	2.1	5.4	—	—	2.5	2.2	2.7	5.5
5	—	—	—	70.0	74.9	71.1	4.5	1.4	3.3	9.7	6.6	9.7	—	—	—	26.7	13.9	27.3
6	—	—	—	38.4	148	97.8	—	3.2	10.8[f]	15.4	12.4	16.5[f]	—	—	—	15.2	28.7	16.2
7	—	—	—	42.0	49.6	51.1	—	—	—	21.7[g]	30.0[f]	25.3[f]	—	—	—	21.2	28.9	24.2
8	—	—	—	1.4	1.2	1.3	—	—	—	2.4	2.6	2.4	—	—	—	1.6	1.6	1.6
9	5.1[f]	—	—	33.6[f]	36.8[f]	43.6	2.9	3.0	16.7	14.6	18.6	23.7	—	—	—	2.6	2.3	7.1

a. Data on the coefficient of variation have been previously given.[12]

b. Longitudinal direction.

c. Transverse direction.

d. Diagonal direction.

e. The lines indicate that the peak load occurred essentially at the ultimate elongation.

f. Average of four tests.

g. Average of three tests.

***Table 4** Elongation of membrane samples used in the determination of the revised criterion, percent[a]*

Sample no.	73°F (23°C)						0°F (−18°C)						−30°F (−34°C)					
	At peak load			Total			At peak load			Total			At peak load			Total		
	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]
1								—[e]			3.2 (14.0)							
2								—			4.0 (17.6)							
3	4.3 (19.3)	2.2 (9.6)	20.6 (91.5)	26.7 (119)	11.3 (50.1)	25.1 (112)	—	—	5.0 (22.2)	4.6 (20.2)	3.3 (14.7)	10.1 (44.7)	—	—	1.7 (7.6)	6.1 (27.1)	3.6 (15.8)	5.1 (22.5)
4	2.3 (10.4)	2.6 (11.6)	16.4 (73.1)	17.3 (76.9)	15.4 (68.6)	19.0 (84.5)	—	—	3.2 (14.0)	3.2 (14.0)	2.8 (12.2)	3.9 (17.3)	—	—	1.3 (5.8)	3.9 (17.3)	3.4 (14.9)	3.4 (14.9)
5	—	—	—	23.3 (104)	18.4 (82.0)	21.9 (97.2)	2.2 (9.7)	0.5 (2.1)	1.5 (6.5)	4.3 (19.0)	2.1 (9.3)	4.0 (17.6)	— —	— —	— —	11.3 (50.1)	4.3 (19.3)	10.2 (45.3)
6	—	—	—	17.4 (77.5)	16.3 (72.4)	18.3 (81.3)	—	0.9 (3.9)	4.7[f] (21.1)	12.6 (56.2)	2.9 (13.0)	7.2[f] (31.8)	—	—	—	10.9 (48.4)	6.7 (30.0)	5.5 (24.7)
7	—	—	—	19.3 (85.1)	29.7 (132)	23.7 (106)	—	—	—	18.7[g] (83.2)	31.3[f] (139)	22.1[f] (98.5)	—	—	—	15.9 (70.5)	28.6 (127)	20.9 (92.8)
8	—	—	—	1.0 (4.2)	0.6 (2.7)	0.6 (2.7)	— —	— —	— —	4.2 (18.5)	4.2 (18.5)	4.0 (17.6)	— —	— —	— —	2.3 (10.0)	1.8 (8.0)	1.9 (8.2)
9	3.2[f] (14.2)	—	—	22.3[f] (73.1)	16.4[f] (96.0)	21.6 (99.1)	3.6 (15.9)	2.6 (11.5)	21.6 (96.0)	23.3 (104)	22.4 (99.8)	30.6 (136)	—	—	—	5.1 (22.5)	3.4 (15.1)	13.0 (57.8)

a. Data on the coefficient of variation have been previously given.[12]
b. Longitudinal direction.
c. Transverse direction.
d. Diagonal direction.
e. The lines indicate that the peak load occurred essentially at the ultimate elongation.
f. Average of four tests.
g. Average of three tests.

Table 5 *Strain energy per unit gage length of the membrane samples used in the determination of the revised criterion, lbf•in./in. (N•m/m)[a]*

Interply bitumen	Tensile strength lbf/in. (kN/m)	Ultimate elongation %	Strain energy lbf•in•/in. (N•m/m)	Comment
Asphalt	287 (50.3)	1.5	3.2 (14.0)	Strain energy determined in the present study.
Asphalt	267 (46.8)	2.1	3.9 (17.3)	Strain energy estimated from Mathey and Cullen data.[6]
Asphalt	208 (36.4)	1.9	2.8 (12.5)	Strain energy estimated from Rissmiller data.[25]
CT pitch[1]	265 (46.4)	0.9	1.7 (7.6)	Strain energy estimated from Mathey and Cullen data.[6]
CT pitch	181 (31.7)	3.8	4.9 (21.8)	Strain energy estimated from NRCA data.[23]
CT pitch	305 (53.4)	1.6	3.5 (15.6)	Strain energy estimated from Rissmiller data.[25]

1. Coal tar pitch

Table 6 *Tensile strength, elongation, and strain energy of typical four-ply organic built-up membranes*

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 lbf/in. (35 kN/m) in the weaker direction (longitudinal or transverse) of the membrane when tested at 0°F (−18°C). OR The strain energy shall not be less than 3 lbf•in./in. (13 N•m/m) in the weaker direction (longitudinal or transverse) of the membrane when tested at 0°F (−18°C); in addition, the membrane shall remain watertight after elongation at 0°F (−18°C) to a percent at which the strain energy is equivalent to the criterion strain energy of 3 lbf•in./in. (13 N•m/m).
Test	ASTM D 2523, Testing load-strain properties of roof membranes.
Commentary	Certain membranes exhibit anisotropic behavior. Therefore, the results of tests in the weaker direction should apply. For conventional bituminous built-up membranes, the transverse direction is usually weaker; whereas for the new membrane materials, the weaker direction may be either longitudinal or transverse. Excessive elongation of the membrane may cause cracking of the interply bitumen and loss of watertightness. Thus, a watertightness test is conducted at a percent elongation corresponding to the minimum strain energy. The watertightness test used in the present study was based on that given in the CGSB Standard for polymer-modified bitumens. Because of difficulties encountered in conducting this test, it is suggested that, for future application of the proposed criterion, another test be used or an improved watertightness test be developed.

Table 7 *Rcvised performance criterion for load-elongation properties*

Sample no.	Weaker direction	Conformance to tensile strength	Conformance to Strain energy	Conformance to Watertightness
1.	T[1]	Yes	Yes	Not needed[3]
2.	T	Yes	Yes	Not needed[3]
3.	T	Yes	Yes	Not needed[3]
4.	T	Yes	No	Not needed[3]
5.	T	No	No	Not needed[4]
6.	T	No	No	Not needed[4]
7.	L[2]	No	Yes	Yes
8.	T	Yes	Yes	Not needed[3]
9.	T	No	Yes	Yes

1. Transverse direction.
2. Longitudinal direction.
3. The watertightness test is not needed since the membrane specimen conforms to the criterion for tensile strength.
4. The watertightness is not needed since the membrane specimen does not conform to either the tensile strength or strain energy criterion.

Table 8 *Comparsion of the properties of the membrane samples with the revised performance criterion*

Sample no.	Tensile strength peak load lbf/in. (kN/m)	Elongation ultimate percent	Strain energy total lbf•in./in. (N•m/m)
10	72.5 (12.7)	19.6	12.6 (55.8)
11	77.6 (13.6)	20.9	14.9 (66.4)
12	141 (24.7)	11.4	11.8 (52.5)
13	190 (33.3)	12.9	17.6 (78.3)

a. Average of three tests. Tests were conducted at 0°F (−18°C) in the transverse direction of the sample.

Table 9 *Load-elongation properties of additional samples tested in comparison to the strain energy criterion*

Membrane characteristic	Membrane type[1]: Two-ply polyester	Membrane type[1]: Two-ply polyester	Membrane type[1]: One-ply type IV glass/ Two ply polyester
Interply bitumen	Type III asp.	Type III asp.	Type III asp.
Flood coat	Yes	Yes	Yes
Polyester mass	5.3 oz/sq yd	5.3 oz/sq yd	5.3 oz/sq yd
Age, years	2	0.5	0.5
Tensile strength	184 lbf/in. (32.3 kN/m)	145 lbf/in. (25.4 kN/m)	119 lbf/in. (20.9 kN/m)
Elongation	38.1 percent	37.8 percent	42.6 percent
Strain energy	56.5 lbf•in./in. (251 N•m/m)	41.1 lbf•in./in. (182 N•m/m)	34.0 lbf•in./in. (151 N•m/m)
Watertightness[2]	Yes	Yes	Yes

1. Load-elongation properties were measured at 0°F (−18°C).[26]
2. Watertightness conducted with a 6 in. (150 mm) head of water.[26]

Table 10 *Field data for polyester-based built-up membranes* [26]

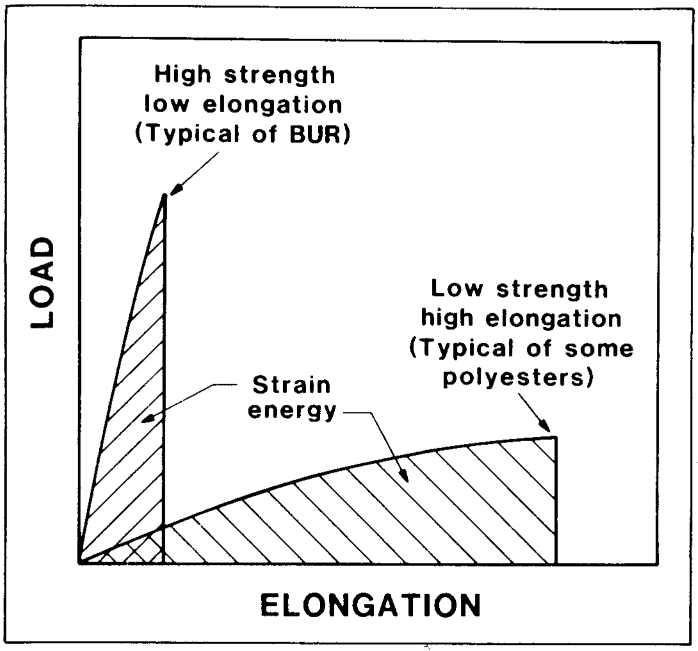

Figure 1 Comparison of strain energy for materials having variable load-elongation properties

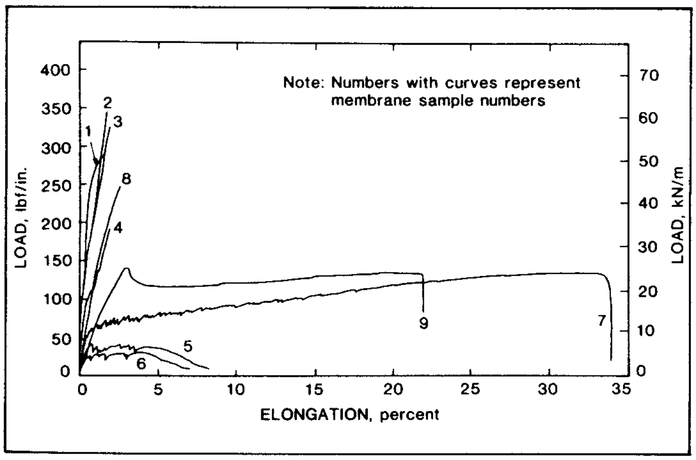

Figure 2 Load-elongation curves of the membrane samples, when tested at 0° F (−18° C) in the transverse direction

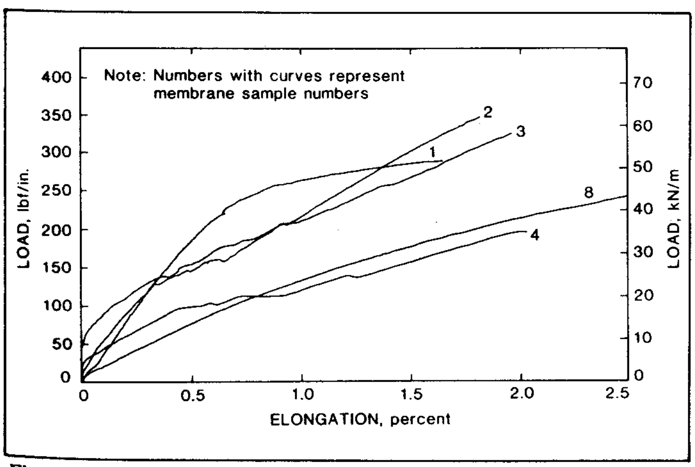

Figure 3 Illustration showing that the load-elongation properties of some new bituminous membranes are comparable to those of conventional built-up membranes, when tested at 0° F (−18° C)

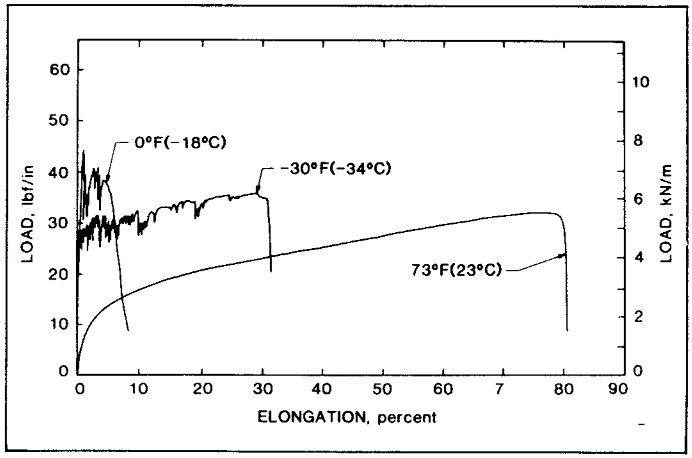

Figure 4 Load-elongation curves for sample no. 5, when tested in the transverse direction at 73, 0, and -30 °F (23, −18, and -34° C)

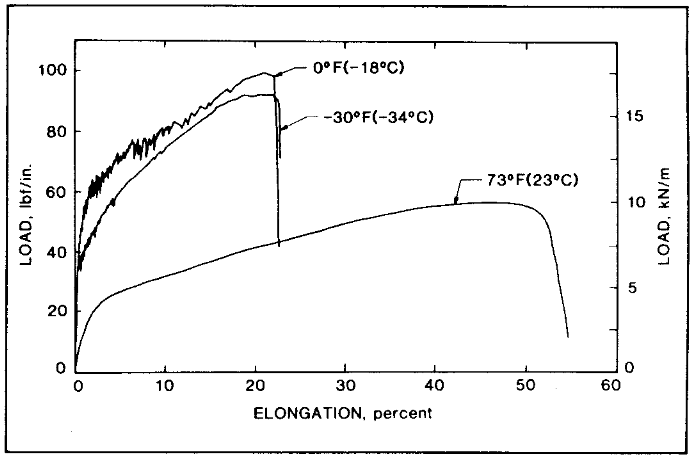

Figure 5 Load-elongation curves for sample no. 7, when tested in the longitudinal direction at 73, 0, and -30 °F(23, −18, and -34° C)

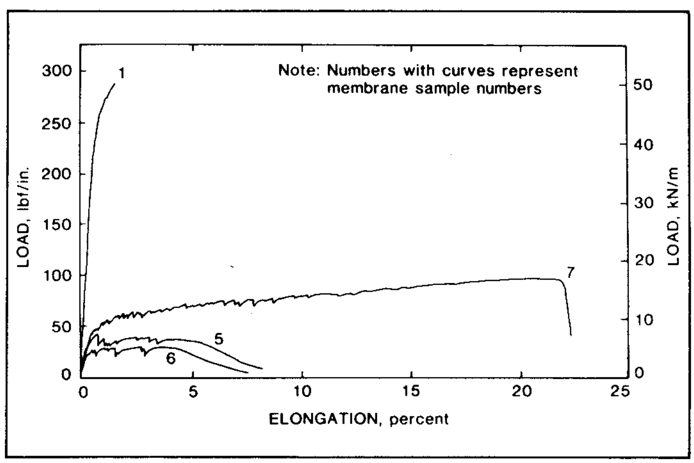

Figure 6 Comparison of the load-elongation curves of the polyester samples with that of the organic membrane sample; tests are compared for the weaker direction of the membrane sample at 0° F (−18° C)