EVALUATION, TESTING AND STANDARDS FOR MODIFIED BITUMEN

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Webster's[1] defines:

evaluation: to examine and judge the worth, quality and significance of something.

standard: a) something that is established by authority, custom or general consent as a model to be followed. b) a definite level or degree of quality that is proper and adequate for a specific purpose.

testing: the act or process that reveals inherent qualities (as of character).

Evidently, the act of testing a material to a standard is related to the evaluation of that material.

In the last 15 years roofing technology has progressed well. The successes of new and very different roofing systems have challenged and defeated some of the "old truths" about flat roofing, but the failures of other new materials indicate that our industry still has a lot to learn.

Given that consensus standards rarely, if ever, reflect the current level of knowledge and that this knowledge is incomplete, we are left with the sorry truth that any roofing material cannot be considered to have proven its worth until it has been successfully used in service. On the positive side, the move toward performance-related standards helps to reduce the risk of roof failures by the identification of key performance attributes and criteria.

EVALUATION

"To examine and judge the worth, quality and significance of something."

More often than not, two roofing experts will evaluate roofing materials and roofing systems differently. Experience, knowledge and ability are key ingredients in any evaluation and each person is different in these respects. Because of these differences the concept of developing consensus standards promises to result in widely accepted, if somewhat compromised, standards.

Standards can be used as a yardstick when evaluating the quality of a material or the quality of application of a material. This paper concentrates on material standards and leaves application standards to those more expert in that field. Some excellent videocassette presentations are available from the NRCA,[2] ARMA[3] and some individual manufacturers and contractors that show how to apply modified bituminous materials.

Although this paper focuses on material standards, this does not indicate that one can divorce materials from application considerations. Probably the most important problem in standards-writing committees is the lack of representation from applicators. Sometimes it might be of benefit to hold an ASTM meeting huddled around an asphalt kettle on a −30°C (−22°F) day in Montréal in February. The realities of hot asphalt setting in seconds, roofing nails freezing the skin off fingers and the like can soon be forgotten in a cozy meeting room.

STANDARDS

"a) Something that is established by authority, custom or general consent as a model to be followed. b) A definite level or degree of quality that is proper and adequate for a specific purpose."

Standards are desirable for product acceptance in the marketplace because they give distributors and users some assurance of product quality. Standards promote an orderly market, assure buyers of a certain product quality or suitability, and protect producers and distributors from quality-cutting competitors.

Type of standards

Standards can be vouluntary or mandatory. Voluntary standards are developed by interested parties. However, many voluntary standards become mandatory when they are referenced by a government agency. For example, building codes frequently reference voluntary standards developed by ASTM and other standards-writing organizations. These referenced standards then have the force of law. Most building material stardards are voluntary, but end up as mandatory via their adoption by building code authorities.

Material standards are either commodity- (product) or performance-related. The trend is toward performance standards, with commodity standards being used mainly for manufacturing quality control. Performance standards are written for products with specific end uses and focus on product performance in laboratory tests developed to indicate product performance in actual use. Probably the most important part of developing performance standards is the identification of end-use requirements and the translation of these requirements into appropriate laboratory tests.

The move from commodity to performance standards is an evolutionary process. While the roofing industry writes different standards for membrane materials that ultimately have the same end-use, it is difficult to believe that we are really in a position to identify *all* end-use requirements *and* successfully translate these requirements into appropriate laboratory test methods and acceptance criteria. The roofing material standards of today might be termed material characterization standards, as the only real performance being measured is the performance of materials in laboratory tests. However, as standards-writing organizations continue to identify the physical properties that are more relevant to end-use, we will find that future material characterization standards are truly performance standards.

National standards

As of March 1986, an international CIB and RILEM technical committee[4] listed the modified bituminous roofing material standards of Western Europe and North America. These are contained in Table 1. It is interesting to compare these national standards and how they are used by the roofing industries of each country.

Cullen has written an excellent review article[5] entitled "The Role of Research in Standards" and in this, he describes the European Union of Agrément (UEAtc or the Union Européenne pour l'Agrément technique dans la construction) system.

The Agrément system is extensively used in countries like Britain and embodies an Agrément Board which has a mandate to evaluate building materials and to determine whether, in its opinion, these materials are likely to provide a service life of at least 10 years. A team of Agrément roofing technology experts will evaluate materials using any and all information at hand, the most valuable being in-service history and the second most valuable being the Agrément standards. Much of the Agrement standard relates to evaluating material properties after a significant (up to six-month) period of artificial aging, and the number of tests employed is extensive.

In North America, the standard most often referred to for modified bituminous roofing is the Canadian General Standards Board (CGSB) document. In Canada, most material manufacturers, distributors and users refer to this standard. Many of the test methods employed in the CGSB standard are based on European tests as our European colleagues had, and continue to have, a great impact on the North American modified bituminous roofing membrane industry.

The MRCA MB-30 standard was widely read in the February 1984 issue of *RSI.*[6] This technical document recommended standards for each phase of the construction: the material manufacturing, the application, and the final performance of modified bituminous systems. It also pointed out that absolute performance criteria for roof membranes are only possible if each roof system assembly is fully understood in engineering terms.

Physical properties required in standards

Table 2 contains a comparison of the physical properties specified in the European Agrément, the Canadian general Standards Board and the Midwest Roofing Contractors Association's Recommended Performance Criteria standards. Because of the different testing procedures used, it is somewhat misleading to compare the criteria for acceptance used by each organization. However, it is interesting to list those properties that all three organizations considered important when writing these documents.

- Resistance to the transmission of liquid water.
- Thermal stability (of metal-faced materials).
- Resistance to repeated opening and closing of a crack in a substrate.
- Resistance to static puncture.
- Resistance to dynamic puncture.
- Lap-joint strength, for both new and aged materials.
- Breaking strength.
- Elongation at break.
- Cold-temperature flexibility.

By virtue of being measured twice (i.e., new and aged) the single most important property would appear to be lap-joint strength. It is encouraging to note that the international CIB/RILEM working commission members listed defective laps as one of the most prevelant problems in 12 of 13 countries. This information is contained in Table 3.

An approach to standards development

In moving from commodity standards toward performance standards, we have moved from the concept of, "What material characteristics can we easily measure?" to "What (measurable) physical properties are required for performance?"

On a purely technical basis, there are few people who would argue that if a physical property is required from new material then it is required from aged material; for without this how can we assess durability? By the same logic, if we measure a property at 21°C (70°F), then we should also measure it at rooftop temperatures to determine any climatic restrictions. Obviously, the permutations and combinations of material and test conditions are endless; equally obvious is that this approach is commercially unacceptable to the industry.

The compromise is to ask the question "What (measurable) physical properties are the *most* relevant to performance?" To avoid this question could result in exceptionally involved and/or irrelevant standards. To answer this question will result in short, relevant standards, which will not be foolproof but which will go a long way toward ensuring that only quality materials conform.

To identify the most relevant performance requirements, it is necessary to assemble a list of performance problems that can be ameliorated by improving a physical characteristic of the material. This list of performance problems ensures that the focus is on the most relevant performance requirements. In many cases, a complete solution to the problem can only be accomplished in concert with improved design and site practice. It is important to maintain a distinction between those performance problems and performance requirements that can be significantly addressed by improving materials, and those where the solution lies elsewhere.

The selection of the most important performance requirements is the foundation for standards development. This selection process is best undertaken by as wide a group of knowledgeable individuals as possible, especially if the performance history of the materials is limited. Once the most relevant performance requirements have been selected, material scientists and engineers can translate these into material properties and suitable test methods to determine these properties. The last stage in the process is the most difficult: this is the selection of criteria for acceptance.

The process of development of standards can be viewed sequentially:

1. Identify the need for a standard and, if it exists, form the appropriate group of individuals.
2. Define the standard's scope.
3. Look at the performance of materials on a roof and identify the most important requirements.
4. Relate on-the-roof requirements to the physical properties of materials.
5. Consider the most appropriate test methods to evaluate these physical properties.
6. Assess the reproducibility of test methods in a round-robin evaluation.
7. Select pass/fail criteria.
8. Write the standard.

TESTING

"The act or process that reveals inherent qualities (as of character)."

In the step-by-step development of a standard, a detailed knowledge of testing procedures is essential for only two steps (5 and 6), but an understanding of the behavior of materials in laboratory tests is very important to:

(Step 4) Relate on-the-roof requirements to the physical properties of materials.

(Step 5) Consider the most appropriate test methods to evaluate the aforementioned physical properties.

(Step 6) Assess the reproducibility of test methods in a round-robin evaluation.

(Step 7) Select pass/fail criteria.

Relating performance requirements to physical properties of materials

The performance of modified bituminous roofing membranes has been generally good in many countries, as indicated in Table 3. Both Canada and the United States have experienced similar performance problems: defective laps, blistering, splitting, delamination and shrinkage. In addition to these problems, the long-term durability of modified bitumens in a North American environment is still not proven.

Table 4 contains some of the relationships between the physical properties of membrane materials and the requirement to have watertight laps, blister resistance, resistance to splitting, delamination resistance, shrinkage resistance and durability. The listed relationships are not exhaustive, but it is interesting to note that only one quarter of the physical properties listed involve measurements on new and dry material at 21°C (70°F). As few roofing problems arise under mild and dry conditions with new materials, this result might have been anticipated.

A more detailed consideration of two performance requirements may illustrate the relationship between the requirements and the physical properties of a membrane as measured in a laboratory.

Resistance to splitting When a sample of modified or oxidized bitumen is cooled, the tensile strength increases and the elongation at break decreases. In short, it becomes more brittle. The degree of embrittlement varies from product to product, but at very cold temperatures, the mechanical properties of modified and oxidized bitumens can be indistinguishable.

The low tensile strength of the glass mat (50 g/m^2 = 1 lb/100 ft^2) reinforcement used in the two-ply modified membrane is more than compensated by the high elongation in moderate climates. This is not the case for the glass mat (100 g/m^2 = 2 lb/100 ft^2) reinforced two-ply BUR membrane. At −40°C (−40°F), however, the two-ply BUR membrane has the better mechanical properties.

		2-ply glass reinforced modified bitumen membrane (50 g/m^2 = 1 lb/100 ft^2 glass mat)					**2-ply glass felt BUR membrane (experimental sample) (100 g/m^2 = 2 lb/100 ft^2 glass mat)**				
Temperature		**Tensile Strength**		**Elongation at Break***	**Strain Energy**		**Tensile Strength**		**Elongation at Break***	**Strain Energy**	
(°C)	**Direction**	**(kN.m^{-1})**	**(lbf.in^{-1})**	**(%)**	**(kN.m^{-1})**	**(lbf.in^{-1})**	**(kN.m^{-1})**	**(lbf.in^{-1})**	**(%)**	**(kN.m^{-1})**	**(lbf.in^{-1})**
21	MD	7.6	(43)	36.0	0.25	(1.4)	17.1	(98)	2.6	0.22	(1.3)
(70°F)	CD	4.9	(28)	92.0	0.19	(1.1)	14.7	(84)	2.5	0.19	(1.1)
−40	MD	25.1	(143)	1.9	0.24	(1.4)	29.7	(170)	2.3	0.34	(1.9)
(−40°F)	CD	17.2	(98)	1.6	0.14	(0.8)	25.8	(147)	2.3	0.30	(1.7)

* Break was defined as that point when waterproofing properties were lost.

Both membranes, when restrained from contraction (as on a fully adhered roof), developed thermal loads of approximately 4 kN.m^{-1} (23 lbf.in^{-1}) when cooled from 21°C to −40°C (70°F to −40°F). This amount of load reduces the tensile strength and strain energy available to cope with any mechanical movements at −40°C (−40°F). The resulting values of residual tensile strengths and residual strain energies give a more accurate picture of a membrane's resistance to splitting at low temperatures. In the above comparison, the values at −40°C (−40°F) become:

		Residual tensile strength		**Elongation at break**	**Residual strain energy**	
Membrane	**Direction**	**(kN.m^{-1})**	**(lbf.in^{-1})**	**(%)**	**(kN.m^{-1})**	**(lbf.in^{-1})**
2-ply glass reinforced modified bitumen membrane (50 g/m^2 = 1 lb/100 ft^2 glass mat)	MD	22.0	(126)	1.9	0.21	(1.2)
	CD	13.9	(79)	1.6	0.11	(0.6)
2-ply glass reinforced BUR membrane (Experimental sample) (100 g/m^2 = 2 lb/100 ft^2 glass mat)	MD	26.2	(150)	2.3	0.30	(1.7)
	CD	21.3	(122)	2.3	0.25	(1.4)

Durability Most modified bitumen sheets are reinforced with glass and/or polyester sheets. When these materials are used in roofing membranes they are durable. Glass is strong and brittle at all end-use temperatures, is relatively unaffected by moisture when coated in bitumen and is relatively unaffected by other aggressive environmental agents. Polyester, although not brittle, behaves similarly to glass with the exception that some dimensional change can be expected during application when built-in manufacturing stresses are relieved.

Although the durability of bitumen membranes is affected by the dimensional stability and mechanical properties of the reinforcements, the aging of a membrane is mainly governed by the aging characteristics of the bitumens, both coating and bonding bitumens, and by their protection from aggressive agents (light, heat, water, foot traffic and biological agents).

The criteria selected for the assessment of membrane aging characteristics should address the changing properties of bitumens. As bitumens age, they become more brittle and less extensible. Two tests useful in evaluating the extent of aging are changes in the elongation at break, and low-temperature flexibility. A loss of heat resistance (i.e.,a reduction in the temperature at which the bitumen begins to flow) can also indicate aging.

There are many methods employed to accelerate the aging of roofing membranes and probably no single method can faithfully accelerate the effects caused by nature. Since the excellent work of Martin,[7] there has been much debate over the relative merits of using light, heat or moisture as the aging agent for bitumens. In nature, all three agents have their effects, but the current thinking leans toward heat aging as being the most appropriate. In one paper, May[8] indicated that seven days at 80°C (176°F) is considered to be roughly equivalent to one year of natural exposure in the United Kingdom.

It would appear that it might be possible to rank the rates of aging of modified bitumens by plotting the changes in low temperature flexibility, elongation at break and heat resistance as a function of time. Further, this ranking process might be speeded up by monitoring the changes in these properties at 80°C (176°F).

Selection of the most appropriate test methods

The most appropriate test method for the measurement of any physical property is one which is the most realistic, relevant, economical and reproducible. There are some test methods that meet these four requirements, e.g.,flexibility tests, and some that do not, e.g.,tensile strength tests.

It is interesting to compare these two tests:

Realism: Bending the membrane around a flexibility test mandrel duplicates roof conditions when constructing flashings.
The tensile tester grips the material on both faces and pulls only in one direction. This is not the way roof stresses are imparted to the membrane (they usually occur through one face and in all directions).

Relevancy: Flexibility is an advantage when it comes to handling and detailing. It can also be used to evaluate aging characteristics. Tensile strength has a major influence on splitting resistance, whether it be caused by ice[9] or substrate movements.[10]

Cost of Test: Flexibility test apparatus costs less than $1,000.
Tensile test apparatus costs more than $10,000.

Reproducibility: Flexibility tests are usually reproducible within ±3°C (±5°F).

Tensile strength tests are usually[11] reproducible within ±10% at 21°C (70°F) and ±20% at −30°C (−22°F).

It is important to strive for cheap and realistic tests, but relevancy and reproducibility are probably more important considerations. A test result is useless if it is irrelevant or irreproducible.

Determination of test method reproducibility

The repeatability of a test method can be evaluated in one laboratory, as it is simply related to the difference between individual results when the same operator, using the same machine, tests individual specimens from the same sample of material following the same procedure. By its nature, repeatability reduces errors introduced by different operators, testing machines and samples.

The reproducibility of a test method is related to the differences found between the results when different operators use different testing machines to test specimens from the same sample of material following the same procedure. Reproducibility, or rather lack of it, is much better determined in a round robin involving as many interested parties as possible.

For meaningful standards round-robin evaluations of test methods are essential, although it does mean that the rate of progress is governed by the slowest participant.

Selection of pass/fail criteria

Inevitably, this is the sharp end of standards writing. It is a particularly thorny issue when it comes to writing consensus standards because of different views, experiences and interests of the committee members.

The purpose of a standard is to try to ensure ourselves, the buying public, that merchandise which is fit for its intended purpose is bought and sold. There is room, in countries with various climatic regions, to classify weather-exposed building materials such as roofing membranes on their ability to perform regionally. In my view, there is no room to lower acceptance criteria to the point where all materials meet the standard, in the misguided belief that we are helping everyone.

REFERENCES

[1] *Webster's Third New International Dictionary*, Unabridged Version, C & C Merrian Co. (1964).

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[3] ARMA "A Guide to Safety: Torching On Modified Bitumens," an audiovisual and written presentation, Asphalt Roofing Manufacturers Association (1986).

[4] CIB/RILEM, "Elastomeric, Thermoplastic and Polymer Modified Bituminous Roofing," Report from the CIB Working Commission W.83 and the RILEM Technical Committee 75-SLR, March (1986).

[5] W.C. Cullen, "The Role of Research in the Standards Development Process," ASTM Symposium on Roofing Research and Standards, ASTM D-8 Committee, December (1986).

[6] MRCA "Performance Criteria for Modified Bitumens," Midwest Roofing Contractors Association, *RSI* magazine, February (1984).

[7] K.G. Martin, "Evaluation of the Durability of Roofing Bitumens," *J. Appld. Chem.*, 423-435, *14*, (1964).

[8] J.O. May, "Temperature Profiles of Different Roof Waterproofing Systems Subjected to Natural Exposure Conditions," *Proc. Second Intl. Symp. on Roofing Technology*, RILEM/NBS/NRCA,80-85, (1985).

[9] R.G. Riedel, "A Theory to Explain Roof Splitting by Ice," *Proc. Second Intl. Symp. on Roofing Technology*, RILEM/NBS/NRCA, 112-115, (1985).

[10] M. Koike, "Elastic Analysis on Ruptures of Bitumen Felt Roof Coverings Caused by Cracks in Substructures," Occasional Report No. 15, Building Research Inst., Tokyo, Japan (1963).

[11] Results from an ongoing Canadian General Standards Board round robin of test methods.

No.	Origin	Designation	Date	Title
1.	Canada	CGSB 37-GP-56M	7/1980	Standard for: Membrane, Modified Bituminous, Prefabricated and Reinforced for Roofing
2.	Europe	UAEtc MOAT 27	1/1983	General Directive for the Assessment of Roof Waterproofing Systems
3.	Europe	UEAtc MOAT 30	8/1984	Special Directives for the Assessment of Reinforced Waterproof Coverings of Atactic Polypropylene (APP) Polymer Bitumen
4.	Europe	UEAtc MOAT 31	8/1984	Special Directives for the Assessment of Reinforced Homogenious Waterproof Coverings of Styrene-Butadiene-Styrene (SBS) Elastomeric Bitumen
5.	Finland	SFS 5010	—	Requirements for Bitumen and Elastomer Bitumen Felts (In Preparation)
6.	Finland	SFS 5011	—	Test Methods for Bitumen and Elastomer Bitumen Felts (In Preparation)
7.	Norway	NS 3530	1985	Proposed Standard for Sheet Applied Polymer Modified Bituminous Waterproofing Materials
8.	USA	MRCA MB-30	11/1983	Recommended Performance Criteria for Modified Bitumen Roof Membrane Systems (Prefabricated and Reinforced)
9.	West Germany	DIN 52132	—	Polymer Bitumen Sheeting for Waterproofing Roofs
10.	West Germany	DIN 52133	—	Polymer Bitumen Waterproofing Sheeting for Fusion Welding
11.	West Germany	DIN 16729	8/1982	Sheets of Ethylene Copolymer Bitumen

Table 1 *National standards and related documents for modified bituminous roofing materials*[4]

UAEtc[1]	CGSB	MRCA
Resistance to fire		Resistance to fire and burn damage.
Resistance to pull-off under suction		Resistance to wind uplift.
Resistance to peel		
Resistance to water pressure	Watertightness test.	Water transmission resistance.
Resistance to thermal shock		Temperature-induced load—new and aged.*
Dimensional stability (includes thermal stability)	Thermal stability (a test for metal foil faced materials only).	Dimensional stability (and thermal stability).
Resistance to sliding		Resistance to sliding.
Resistance to cyclic movement—new and aged*	Crack bridging capability.	Crack bridging ability.
Resistance to static indentation	Resistance to static puncture.	Resistance to static puncture.
Resistance to dynamic indentation	Resistance to dynamic impact.	Impact resistance (dynamic).
Water vapour permeability	Water vapour transmission.	
Resistance to tear		
Air leakage in single-ply joints—new and aged*		
Tensile (shear) strength of single-ply joints—new and aged*	Lap joint strength—new and aged.*	Lap joint strength and elongation—new and aged.*
Unrolling at low temperatures		
Tensile strength	Breaking strength—new and aged.*	Tensile strength—new and aged.*
Elongation at break	Elongation at break—new and aged.*	Elongation at break—new and aged.*
	Load-strain product—new and aged.*	Strain energy—new and aged.*
Cold temperature flexibility—new and aged*	Cold temperature flexibility.	Cold temperature flexibility.
Heat resistance—new and aged*		
	Water resistance (absorption).	Water resistance (absorption).
	Granule embedment.	Granule embedment.
	Resistance to accelerated weathering.	Resistance to accelerated weathering.
		Abrasion resistance.

[1] Other tests relating to individual components (e.g. reinforcement alone or bitumen coating alone), material compatibility, resistance to biological attack, etc, have been omitted.

*Aged refers to accelerated/artificial aging.

Table 2 *Physical properties specified in the UAEtc, CGSB and MRCA standards*

Information	Australia	Canada	Denmark	England	Finland	France	Israel	Italy	Japan	Norway	Switzerland	USA	W. Germany
1. Types used													
APP-modified	S	S	S	F	N	S	S	F	S	S	S	F	S
SBS-modified	S	F	F	S	F	F	S	S	S	F	F	F	F
Other modifiers	—	S	N	—	N	S	—	—	—	—	—	S	—
2. Configuration													
Single layer	—	F	N	S	N	S	F	F	F	S	F	F	N
Two layers	—	F	F	F	F	F	—	F	S	F	F	F	F
More than two	F	N	N	S	S	N	—	N	S	S	—	N	S
3. Application methods													
Hot-applied adhesive	F	F	F	F	F	F	—	N	S	F	F	F	F
Cold-applied adhesive	S	S	F	S	N	S	—	S	F	—	—	S	S
Torching	S	F	F	F	S	F	F	F	N	S	F	F	F
Other	—	S	N	—	—	S	—	S	—	S	—	—	S
4. Performance													
APP-modified	C	B	B	A	—	A	C	A	B	C	A	B	B
SBS-modified	B	A	B	B	A	A	B	B	B	B	A	B	B
Other modifiers	—	C	—	—	—	D	—	—	—	—	—	—	—
5. Problem experience													
Defective laps	S	S	S	S	S	S	S	S	S	—	N	S	S
Blistering	S	S	N	—	N	S	F	S	S	—	N	S	N
Splitting	S	S	N	—	N	N	—	N	N	—	N	S	N
Delamination	—	S	N	S	N	N	—	N	N	—	S	S	N
Shrinkage	—	S	N	S	S	S	—	N	N	S	S	S	S
Other	—	—	—	—	—	—	—	—	—	—	—	—	—

F: Frequent S: Some N: None —: No response
A: Excellent B: Good C: Fair D: Poor

Table 3 *The usage and performance of modified bituminous roofing membranes in some countries*[4]

Performance requirement	Relevant physical properties of the membrane material	Some other considerations
Watertight laps	1. Shear strength of laps—new and aged. 2. Sheet conformability. 3. Adhesive and sheet compatibility—new and aged. 4. Dimensional stability of sheet.	■ Single or multi-ply. ■ Loose or attached membrane. ■ Rolls stored on end, with selvedge edges up. ■ No water bucking on laps.
Blister resistance	1. Peel strength, sheet to sheet and sheet to substrate—new and aged. 2. Sheet conformability. 3. Adhesive and sheet compatibility—new and aged. 4. Moisture absorption and adsorption characteristics of sheet.	■ Moisture present during application. ■ Moisture present in substructure. ■ Correct asphalt application temperature (not so heavy as to skip-mop). ■ Cold conditions (some sheets lose conformability). ■ Heavy or lightweight surface covering. ■ Roof drainage.
Resistance to splitting	1. Residual* tensile strength, elongation at break, and residual strain energy—new and aged—wet and dry—high and low temperatures. 2. Shear strength of adhesive—new and aged—wet and dry—high and low temperatures. 3. Dimensional stability of sheet. 4. Low temperature flexibility.	■ Loose or attached membrane. ■ Conventional or IRMA roof. ■ Roof ice build up (drainage). ■ Solid attachment at details. ■ Substrate material uniformity.
Delamination resistance	1. Shear and peel strength of manufactured coatings to reinforcement—new and aged. 2. Shear strength, sheet to sheet and sheet to substrate—new and aged. 3. Dimensional stability of sheet.	■ Same considerations as for blister resistance.
Shrinkage resistance	1. Dimensional stability of sheet.	■ Correct attachment. ■ Adequately wide side and end laps.
Durability	1. Low temperature flexibility—new and aged. 2. Heat resistance—new and aged. 3. Elongation at break—new and aged. 4. Puncture resistance. 5. Abrasion resistance. 6. Granule coverage—new and aged. 7. Thermal stability of metal surfacing.	■ Surface protection. ■ Roof drainage. ■ Moisture presence. ■ Quality of roof design and application.

*Residual tensile strength at a given temperature = tensile strength at this temperature minus the thermal load built up when a restrained (or attached) membrane is cooled to this temperature.

Table 4 *Some relationships between roof performance requirements and the physical properties of the membrane material*