DEVELOPMENT OF LABORATORY PERFORMANCE TESTS OF BUILT-UP ROOFING

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INTRODUCTION

A voluminous research effort to identify and evaluate performance attributes of built-up membranes has been under way during the past decade, but practical application of this research has lagged. To accelerate this lagging process of translating these research data for practical use, this paper proposes an abbreviated list of membrane performance attributes, retaining the more critical, eliminating the less critical attributes.

Along with this abridged list (see Figure 8), this paper also proposes development of test methods capable of generating data reproducible by different laboratories. The goal is thus twofold:

- to promote more widespread use of membrane performance criteria
- to assure more dependable, standardized test results.

HISTORICAL BACKGROUND

In 1925, nearly two decades after issuance of the first manufacturer's built-up roof specification, the American Society for Testing and Materials (ASTM) adopted standards for asphalt and tar-saturated felts, and, a few years later, specifications for the mopping bitumens used with those felts. These specifications were prescriptive, not performance-oriented.

In 1950, ASTM adopted E84, the tunnel test, used by Underwriters Laboratories (UL) to evaluate the surface-burning characteristics of building materials. ASTM later adopted E 108, "Fire Tests of Roof Coverings," also used by UL to establish the fire hazard classification of roofing systems exposed to fire on the top surface.

At about the same time, Factory Mutual (FM) Laboratories developed its construction materials calorimeter, which provided fuel contribution rates that correlated well with flame spread ratings obtained by E 84. The calorimeter is used extensively to evaluate fire hazards involved in insulated steel deck constructions.

Factory Mutual also introduced wind-uplift testing in 1956, and though the basic FM test has never been adopted by the ASTM, it is widely used to rate steel deck assemblies. Two other agencies, UL and Construction Research Laboratories, have developed specific uplift tests. The latter is recognized by code-making authorities in hurricane zones, notably southeastern Florida.

These fire and wind-uplift tests utilized by the insurance underwriters and code-making authorities probably represent the first application of performance testing to built-up roofing.

In 1964, William C. Cullen of the National Bureau of Standards (NBS) and the leading proponent of the performance concept as applied to roofing systems, chaired a sub-committee of the Building Research Advisory Board comprising roofing industry experts. The purpose of this committee was to identify for the Federal Housing Authority performance characteristics, appropriate testing procedures, and suitable criteria for acceptance of roof systems. The group prepared a list of 18 characteristics deemed essential to roofing-system performance. They found, however, that existing test methods were available to evaluate only five: 1) fire resistance, 2) wind resistance, 3) flow resistance, 4) resistance to water vapor transmission, and 5) adhesion.

Further investigation revealed that Federal Specification TT-C-520a, although appropriate to measure the flow resistance of prepared roofing and shingles, was not applicable to built-up roof coverings with slag or gravel surfacings. The same was true of ASTM D 903, recommended for the evaluation of adhesion. This left only three characteristics for which existing test procedures were available in 1964.

In 1966, ASTM D 2523 was adopted as a standard method for testing load-strain properties of roofing membranes. Cullen immediately put it to use to evaluate tensile strengths and elongations at failure for various bituminous roofing systems.

Throughout his many years with the NBS Cullen has always stressed the performance concept as opposed to a purely prescriptive approach to standards. Much of his work culminated in the publication in 1974 of ***"Preliminary Performance Criteria For Bituminous Membrane Roofing."***[1] Its purpose: to identify and describe quantitatively the attributes that would assure adequate performance of a bituminous roofing membrane. The twenty attributes represent a slightly modified list from that published in Technical Studies Report #25[2], ten years earlier. Test methods were described for ten of the attributes, and criteria based on those test methods were suggested.

Only the criteria for tensile strength and fire resistance were based on ASTM standard tests. The other eight criteria were based on test methods devised by the NBS, or in the case of wind-uplift resistance, by UL.

In 1976 a special task group was formed within ASTM D

08.20 to develop test methods to evaluate bituminous roofing system performance. This group developed a simple method, ASTM D 3746, for evaluating comparative impact resistance. In addition, it investigated another method for determining thermal shock resistance and still another for tensile/tear strength, or notch tensile, which is similar. The tensile/tear test appears destined for adoption as a standard, but the thermal shock method has not demonstrated the necessary reproducibility from one laboratory to another. NBS has been requested to submit its thermal shock test to this group for evaluation, but so far this has not been accomplished.

Several individuals and laboratories throughout the industry have continued to investigate various performance attributes, and though no other tests have yet been adopted as industry standards, much has been learned about roofing and waterproofing materials. The balance of this paper reviews the 20 performance attributes suggested by NBS BSS55, along with some observation by Jim Walter Research Corp. (JWRC) based on research over the past decade.

MEMBRANE ATTRIBUTES

1. Tensile Strength

Although not a structural element, a roofing membrane must possess sufficient tensile strength to resist the normal stresses imposed by the elements and by normal building movement and traffic over the life of the membrane.

A warm, plastic membrane can accomodate reasonable substrate movement. As temperature drops, however, the membrane becomes more rigid, and because it is restrained, it develops tensile stresses. At the same time, membrane strength increases, so that generally no serious problems occur. Figure 1 shows a typical comparison of the change in tensile strength and development of membrane stresses as the temperature drops from 75° to −100°F. The values have been omitted from the vertical axis because these will vary with the particular membrane under investigation. This graph shows why membranes do not usually tear themselves apart as a result of thermal shock. Membrane strength at any temperature covered by the test conditions always exceeds thermal stress applied.

It is interesting to note that if these curves are extended out to −110°F they would cross. At that point, of course, the stress in the membrane would equal its ultimate strength and a split would occur. The conditions under which this happens, however, could hardly be called typical.

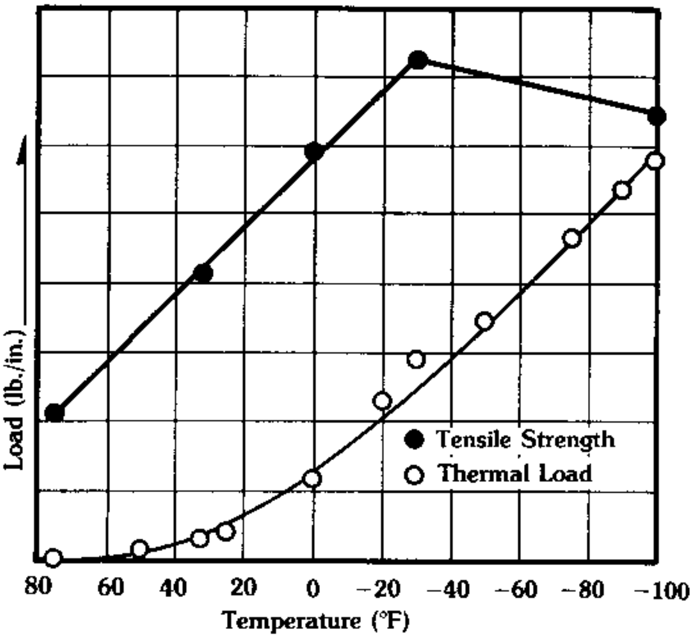

FIGURE 1
Tensile strength and thermal load versus temperature for a typical bituminous roofing membrane.

Many membranes are anisotropic, i.e., they have greater strength in one direction than the other. This fact is accounted for in this paper by providing data for the weakest dimension. Figure 2 shows the cross direction (minimum) tensile strengths and ultimate elongations for several popular roofing membranes at temperatures of 75, 0, and −25°F. Data, obtained via ASTM D 2523, indicate that 200 lb/in. of width at 0°F, as proposed by Cullen and Mathey, is a reasonable value for minimum tensile strength.

2. Thermal Expansion

As shown in Figure 1, healthy membranes do not normally tear themselves apart as a result of thermal contraction alone. Stresses developed in a restrained membrane are significant, however, and when combined with other stresses caused by localized structural movement, or if the membrane is weakened, can produce a split.

The linear coefficient of thermal expansion and contraction is not, we conclude, a performance attribute. Other factors

	TENSILE STRENGTH (lbs./in width)			ELONGATION (%)		
MEMBRANE COMPOSITION	75°F	0°F	−25°F	75°F	0°F	−25°F
4 #15 Tarred Felts in Pitch	73	305	288	3.2	1/6	0.6
4 #15 Asphalt Felts in Asphalt	63	208	224	3.9	1.9	1.1
Base & 3 #15 Asphalt Felts in Asphalt	70	222	234	1.3	1.4	1.2
Base & 3 #15 Asbestos Felts in Asphalt	50	201	248	1.1	1.5	0.8
3 Type IV Glass Felts in Asphalt	146	226	247	1.9	1.8	1.9
4 Type IV Glass Felts in Asphalt	202	337	339	2.1	2.1	2.2

FIGURE 2
Tensile strength and elongation of typical roofing membranes at 75, 0, and −25°F.

must be taken into account in determining resistance to splitting or buckling from changes in temperature.

NBS researchers used this coefficient along with the tensile strength and the modulus of elongation to calculate a given membrane's thermal shock resistance factor.

3. Flexural Strength

Since the roofing membrane is a non-structural element, we conclude that it is clearly a function of the deck and/or the insulation to provide the necessary flexural strength, not the membrane. Membrane movement at buckles or over substrate cracks should be considered as tensile or flexural fatigue.

4. & 5. Tensile and Flexural Fatigue

These, we conclude, are performance attributes, because of localized movement at membrane buckles or over substrate joints. We treat them as a single attribute, because experience indicates that even in flexing, the failure always occurs on the portion of the specimen stressed in tension.

A number of laboratories, in addition to NBS, have been developing a suitable test method to evaluate fatigue in bituminous membranes. Work done at Jim Walter Research Corp. indicates that fatigue resistance is highly dependent upon the magnitude of the membrane stresses. Shapes of stress/strain curves for different membranes are somewhat different, depending on felt type. There is, however, an initial straight-line portion for each curve. As long as stress values used in the fatigue test are taken from this straight-line portion of the curve, fatigue resistance is high. Stresses from the upper portion of the curve (i.e. beyond the elastic limit) produce failure in a relatively short time. It appears obvious to us that considerable additional work is needed to develop an acceptable test method.

	CRACK BRIDGING $\sqrt{TxE}$		
MEMBRANE COMPOSITION	75°F	0°F	−25°F
4 #15 Tarred Felts in Pitch	15.3	22.3	13.2
4 #15 Asphalt Felts in Asphalt	15.7	19.9	15.7
Base & 3 #15 Asphalt Felts in Asphalt	9.5	17.6	16.8
Base & 3 #15 Asbestos Felts in Asphalt	7.4	17.6	14.1
3 Type IV Glass Felts in Asphalt	16.6	20.2	21.6
4 Type IV Glass Felts in Asphalt	20.6	26.6	27.3

FIGURE 3
Crack bridging potential at 75, 0, and −25°F.

Nico A. Hendricks[3], an independent consulting engineer from the Netherlands, has suggested that the crack-bridging ability of bituminous membranes is proportional to the square root of the product of tensile strength and elongation. Since these data are already available in Figure 2, we have done the necessary calculations and include the results in Figure 3 as the crack-bridging potential. Obviously, the higher the value, the more resistant the membrane is to cracking over joints in the substrate.

6. Shear Strength

The NBS, in Building Science Series 55,[4] has proposed certain criteria for verticle punching shear resistance based on an NBS-devised test method. The method evaluates resistances to foot traffic, to ladders placed on the roof surface, etc. NBS has promised to submit its test method to ASTM for round-robin evaluation and consideration for adoption as a standard.

7. Impact Resistance

The hail gun used by the NBS in its studies is undoubtedly the best method available for evaluating actual membrane hail resistance. For simply studying the comparative impact resistance of roofing systems to falling objects such as tree limbs, tools, rocks, etc., ASTM has recently adopted a new standard, D 3746. Figure 4 shows the results obtained at room temperature when our selected roofing systems are subjected to this new ASTM test. The 1-ft-square test specimens are exposed to impact in each of four quadrants and the extent of damage to the membrane is determined by removing the bitumen by extraction with a solvent and examining the individual felts. At JWRC we assign a value of 0 to indicate no damage to the felt, 2 meaning dents in the felt but no breaks, and 4 meaning a break in the felt. All the numbers are added up and divided by four times the number of plies to obtain an average for the specimen. If this value is 3 or greater, it indicates a significant risk of impact damage.

Generally speaking, the softer the substrate beneath the membrane the greater the risk of membrane damage. Smooth-surfaced roofs are also more susceptible to impact damage than gravelled roofs, although occasionally a direct

	GRAVEL SURFACED			SMOOTH SURFACED		
MEMBRANE COMPOSITION	Plywood	15/16" Glass	1" Urethane	Plywood	15/16" Glass	1" Urethane
4 #15 Tarred Felts in Pitch	0	1.5	2.0	—	—	—
4 #15 Asphalt Felts in Asphalt	0.4	0.2	3.5	—	—	—
Base & 3 #15 Asphalt Felts in Asphalt	2.0	3.5	3.4	—	—	—
Base & 3 #15 Asbestos Felts in Asphalt	1.0	0.5	3.2	2.0	4.0	4.3
3 Type IV Glass Felts in Asphalt	—	0	0	—	—	—
4 Type IV Glass Felts in Asphalt	0	—	—	0	3.0	3.8

FIGURE 4
Impact resistance at 75°F.

hit on a gravel particle will drive it into the membrane, breaking some of the plies.

8. Notched Tensile Strength
Tensile/Tear Strength

Due to the many reentrant corners and penetrations associated with skylights, smoke hatches, monitors, curb mounted equipment and the like, stress concentrations occur frequently. These stress concentrations can weaken the membrane locally, to the point where splits and tearing occur. In cold weather these penetrations weaken the membrane in much the same way as a notch cut into the edge of a tensile test specimen.

The Jim Walter Research Corp. has developed a method for measuring the membrane's notched tensile, or tensile/tear strength, using just such a notched specimen. This method has been evaluated by ASTM in a series of round-robins, and it now appears that it will be adopted as a standard in the near future. See Figure 5 for data at 75 and 0°F.

	TENSILE/TEAR STRENGTH (LBS.)	
MEMBRANE COMPOSITION	75°F	0°F
4 #15 Tarred Felts in Pitch	158	573
4 #15 Asphalt Felts in Asphalt	106	345
Base & 3 #15 Asphalt Felts in Asphalt	119	266
Base & 3 #15 Asbestos Felts in Asphalt	110	214
3 Type IV Glass Felts in Asphalt	215	248
4 Type IV Glass Felts in Asphalt	293	326

FIGURE 5
Tensile/tear strength on notch tensile

9. Moisture Effects On Strength

Moisture absorption tends to weaken organic and asbestos felt membranes, sometimes by as much as 60%. Glass-fiber felt membranes may also be weakened significantly, depending on the type of binder employed and the degree of curing. JWRC is developing data on tensile strength of roofing membranes when dry and after prolonged immersion in water at 75°F. Though now unavailable, these data will be published when the tests are completed.

10. Creep

Bituminous roofing membranes are visco-elastic. Over most of the range of loads normally applied, they exhibit linear visco-elastic behavior—i.e., when a load is applied, the total deformation comprises three components: 1) immediate deformation, 2) delayed deformation and 3) viscous flow, all directly proportional to the applied load. Each successive load makes an independent contribution to final deformation, which equals the simple sum of the individual contributions. Total deformation produced by any loading program is almost completely recoverable if the membrane is allowed to relax. The unrecoverable portion is due to viscous flow.

Experiments with membranes in which the felts are continuous for the specimen's full length exhibit no viscous flow (i.e., all of the deformation is recovered completely on removing the load and allowing the membrane to relax). When the felts are not continuous, but simply lapped and cemented together with bitumen, some viscous flow does occur as the felts slide one over the other.

These facts reinforce the argument that normal stresses imposed on a roofing membrane by mild thermal shock or drying out are not cumulative, and that no permanent damage is done to the membrane unless the magnitude of the stress exceeds the proportional limit.

Whereas creep is certainly an important engineering property of the roofing membrane, we see no evidence that it has any adverse effect on performance.

11. Ply Adhesion

Common sense dictates that interply adhesion is an important performance attribute. The presence of voids between the plies creates a porous condition that, if severe enough, may actually lead to seepage of moisture through the laps. At the very least, it creates a potential for interply blistering.

The percent of total area bonded can be assessed in conventional organic and asbestos felt membranes by cooling a 12 × 12 in. roof cut to 0°F, separating the plies, measuring the unbonded areas, and converting this to a percentage of the total cut area. (Unfortunately, this method of separating the plies does not work with many glass felts.) Research at JWRC reveals that for mopping under field conditions, we cannot expect much better than 96-97% adhesion. Performance might well be a function of the size of the individual voids which make up the remaining 3-4%, since earlier research indicates that the pressure required to cause blisters to grow is inversely proportional to the size of the void.

While there are a number of factors affecting adhesion, the most important is the nature of bitumen as a "hot-melt" adhesive. If it is not molten when the felt is embedded, it is not an adhesive. If, on the other hand, it is hot and molten, it will "wet" the felt and effect a bond, despite reasonable quantities of anti-blocking material or moisture. The roofing mechanic has traditionally urged more and more heat in the kettle. This permits him to achieve good production and helps toward maintaining sufficient heat in the mopping to assure good adhesion. If, however, the felt is not embedded close behind the mop, fast cooling may destroy its adhesive qualities.

Another series of tests was run at JWRC in an attempt to assess the asphalt bond as a function of mopping asphalt temperature when the felts were embedded. With asphalt temperature as low as 275°F at the time of embedment, bond strength never fell below 2500 lbs/sq ft when the felts were pulled apart at 75°F. Most roof constructions are only designed to withstand uplift forces of 60-90 lb/sq/ft, and 2500 appears to be adequate. At temperatures near 0°F the mopping asphalt becomes brittle and the interply bond strength drops off a little as failure occurs due to fracture within the moppings. Between 80 and 130°F the felts themselves delaminate, and above 130°F the mopping asphalt fails due to viscous flow. In none of our tests did failure occur at the mopping-felt interface.

Additional work is necessary to develop a suitable performance test. Apparently, you either get a bond or you don't, depending upon the temperature of the mopping bitumen when the felt is embedded. For organic and asbestos felt membranes, the best way to evaluate the bond is through roof cuts as described above.

12. Abrasion Resistance

Little, if any, significant work has been done in the area of abrasion resistance. Except for minor wind scouring at roof corners, abrasion resistance does not appear to pose a serious problem or merit a high priority.

13. Tear Resistance

This has been covered under notched tensile strength. For data on tensile tear strength of representative roof membranes, see Figure 5.

14. Pliability

It is not exactly clear what is meant by pliability. Attachment of the membrane to a rigid substrate with adhesives or mechanical fasteners should pretty much preclude membrane flexing, except at buckles or over joints in the substrate which it can be dealt with under tensile and flexural fatigue.

A loosely laid membrane may flex from wind pressures but again this is largely eliminated by ballast.

15. Permeability

Penetration of liquid water into the membrane should be minimized. This is after all, the primary function of the roofing membrane—to keep water out of the structure. And since the membrane under some conditions functions as a vapor barrier, it should also possess considerable resistance to water vapor transmission. This is one of the few attributes for which a test method was available in 1964. ASTM C 355 is the standard method of test for water vapor transmission of materials having a thickness greater than 1/8 inch, and all of the laboratory-prepared membranes covered in this investigation exhibit essentially zero permeability when the dessicant is placed inside the pan and the pan is placed in a chamber at 50% RH and 75°F.

16. Moisture Expansion

The various types of roofing felt expand somewhat differently when immersed in water long enough to effect complete saturation. Figure 6 shows the equilibrium moisture absorption and the amount of expansion for common felt types.

	PERCENT MOISTURE ABSORBED	PERCENT EXPANSION	
TYPE OF FELT		M.D.	C.D.
Saturated Organic	60-80	0.2-0.5	2.0-2.2
Coated Organic	20-22	0.3-0.4	1.9-2.2
Saturated Asbestos	22-25	.08-.10	0.5-0.9
Impregnated Glass	16-19	.02-.04	0.0-0.0

FIGURE 6
Equilibrium moisture content of roofing felts and associated expansion.

Just as an asphalt coating does not significantly affect the ultimate expansion (only the time required to absorb the necessary moisture), incorporating the felt in a multi-ply membrane with interply moppings of bitumen only increases the time required to accomplish the expansion. If, however, different types of felt are combined into a given membrane, the more dimensionally stable felt tends to reduce the expansion of less dimensionally stable felts. There is also evidence that not all of the felts in a membrane will expand the same amount. There is some horizontal shearing deformation that takes place in warm weather when the interply mopping bitumen is soft enough to permit it.

17. Weather Resistance

This term is so all-inclusive that it is highly doubtful that any one test could ever be devised to assess weather resistance. It is really a summation of all the various individual attributes that collectively constitute weather resistance.

18. Wind-Uplift Resistance

There are, as indicated earlier, test methods available to evaluate uplift resistance. Factory Mutual, Construction Research Laboratories, and Underwriters Laboratories all have standard test methods accepted to one extent or another. Moreover, ASTM is developing a portable nondestructive test procedure that can usually be used in situ.

For most conventional bituminous roofing systems, uplift resistance is more a test of the attachment of the membrane and/or insulation to the substrate, than a test of the membrane itself.

Local and regional building codes, as well as insurance underwriters, have established the specific performance levels considered acceptable, usually 30, 60, or 90 lb/sq/ft, corresponding respectively to true wind velocities of 95, 134, and 164 mph.

19. Fire Resistance

This too is an area where the insurance carriers have established test procedures and acceptable performance. In many cases, these have been adopted by local and regional code making authorities, in such familiar forms as UL Class A, B and C listed roof coverings (via ASTM D 108), FM Class I and II steel roof deck constructions (via the construction materials calorimeter) and UL roof deck constructions (rated via ASTM E 84). These classifications and the test methods by which they are arrived are all quite well accepted in the industry.

20. Fungus Attack Resistance

This attribute probably applies more to residential and commercial roofing involving shingles than to built-up roofing. In low-slope applications, fungus resistance and other bacteriological degradation of a built-up roofing membrane can usually be related to the moisture condition of the roof. Damage to the membrane, other than aesthetic, can be assessed by the loss in tensile strength.

21. Thermal Shock Reistance

Although not included in the list of attributes published in BSS 55, thermal shock was suggested as a preliminary performance criteria. The NBS's thermal shock resistance factor is a (TSF) number calculated by dividing the tensile strength at 0°F (P) of the membrane in question by the product of the modulus of elongation at 0°F (M) and the apparent linear coefficient of thermal expansion for the range of 0 to −30°F (α).

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

This formula is derived from the emperical expression that relates the stress developed in an elastic member restrained so that it cannot contract as temperature drops.

$$S = E\alpha\Delta T$$

S = stress (psi)
E = Youngs modulus (psi)
α = linear coefficient of thermal expansion and contraction (in./in. °F)
ΔT = Temperature change (°F)

The expression assumes a constant modulus and coefficient over the temperature range in question. If this is true, there would be a straight-line relationship between temperature change and the stress developed within the roofing membrane. Investigations at JWRC revealed that this was not true. Both the modulus and the coefficient vary with the temperature. We therefore set out to find another method of evaluating thermal shock. What we ultimately did was to clamp a specimen with a thermocouple attached to it in the jaws of an Instron universal tester fitted with an environmental chamber so that the temperature of the specimen could then be lowered and the resulting stress built up within the specimen recorded. We arbitrarily elected to drop the temperature of the test specimen from 75°F to −25°F in a 30-minute period. This, we concluded, would produce a more severe thermal shock than anything the roof was likely to experience in service. After dropping the temperature to −25°F and recording the load, we activated the jaws of the Instron and broke the specimen at −25°F to determine its ultimate strength. Subtracting the stress developed as a result of dropping its temperature from the ultimate strength gave a number we called residual strength. This we took as a measure of thermal shock resistance, or the additional stresses over and above thermal contractive stress required to fracture the membrane.

Figure 7 shows the cross machine (weaker) ultimate strength, thermal load, and residual strengths for the selected group of roofing membranes at −25°F.

MEMBRANE COMPOSITION	ULT STR.	THERM LOAD	RESID. STR.
4 #15 Tarred Felts in Pitch	299	133	166
4 #15 Asphalt Felts in Asphalt	229	93	136
Base & 3 #15 Asphalt Felts in Asphalt	237	89	148
Base & 3 #15 Asbestos Felts in Asphalt	248	77	171
3 Type IV Glass Felts in Asphalt	228	58	170
4 Type IV Glass Felts in Asphalt	304	79	225

FIGURE 7
Thermal shock resistance

In summary, during the decade of the 1970s, a great deal of effort has gone into identification and evaluation of the various performance attributes of bituminous roofing systems. Unfortunately, it begins to look as though this type of roofing may actually become obsolete before we ever complete our task. It appears fitting therefore, that we streamline the list of attributes to include only the most critical and to concentrate our efforts on development of test methods by which data reproducible from one laboratory to another can be obtained to establish meaningful criteria.

Toward this end, the following list of attributes is proposed (see Figure 8). Where an acceptable test method is available, it is included in the table. Some other test methods are still under development; others have only to be adopted as standards by ASTM.

Tensile Strength & Elongation	**ASTM D 2523**
Tensile & Flexural Fatigue	—
Vertical Punching Shear Resistance	—
Impact Resistance	**ASTM D 3746**
Tensile Tear, or Notched Tensile Strength	—
Ply Adhesion	—
Wind Uplift Resistance	**F.M., U.L., C.R.L.**
Fire Resistance	**U.L., F.M., ASTM E 84 & E 108**
Permeability	**ASTM C 355**
Thermal Shock Resistance	—

FIGURE 8
Abbreviated list of performance attributes

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4. Op Cit. Mathey R. G. and Cullen, W. C.