MECHANICAL PERFORMANCE OF NEW AND NATURALLY WEATHERED BITUMINOUS AND SYNTHETIC SINGLE-PLY ROOFING MEMBRANES

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Waterproofing (roofing) membranes are directly or indirectly susceptible to solar radiation and weathering. The majority of the oxidized bituminous and modified bituminous membranes and the synthetic single-ply membranes, such as plasticized polyvinyl chloride (PVC) and chlorinated polyethylene (CPE), applied to low-slope roofs degrade in some degree due to the presence of solar radiation, including ultraviolet (UV), heat and atmospheric oxygen. These factors commonly result in physical changes that occur in strength, elongation and toughness of the membranes.

A research project* was carried out in the hot-dry climatic region of Saudi Arabia to investigate the performance of low-slope roofs, roofing and insulation materials. A field station was set up to examine the effects of solar radiation and weathering on the waterproofing and thermal insulation materials, and to monitor the surface and the inner temperatures of the applied roof systems.

Various oxidized bituminous and modified bituminous membranes and unreinforced and reinforced plasticized PVC and CPE membranes aged on the roof of the station were physically tested before and after weathering. Weather condition specifically the measured surface temperatures and the applied tests, will be presented in this paper. The subsequent results concerning tensile strength, elongation, strain energy and toughness of these materials will be analyzed, compared and evaluated, and the outcome will be discussed.

KEYWORDS

Artificial weathering, degradation, elongation, modified bituminous membranes, natural weathering, oxidized bituminous membranes, performance standards, single-ply membranes, strain energy, tensile strength, toughness, waterproofing membranes.

INTRODUCTION

Low-slope roofs are subject to severe exposure and, therefore, are susceptible to various environmental problems. Although various roofing systems have been developed to satisfy the different environmental conditions, some roofs in use fail prematurely. Oxidized bituminous membranes, modified bituminous membranes and synthetic single-ply membranes are attacked and deteriorate to some degree by heat from direct solar radiation, near ultraviolet radiation and atmospheric oxidation. These factors commonly result in chemical and physical changes to the membranes.

In Saudi Arabia, as well as in most of the countries with a hot-dry climate and intense solar radiation, low-slope roofs are in common use since they are not exposed to heavy rainfall and snow. However, not all the low-slope roofing systems used have been developed to resist the typical environmental conditions. Some of the roofs do not stand up adequately to the local climate and, thus, deteriorate prematurely.

A field station was built for the research to be carried out in the study titled "Investigation of Roofing and Roofing Insulation Materials in the Hot-Dry Climate of Saudi Arabia."[1] The station was used for testing and weathering a number of oxidized bituminous, modified bituminous and single-ply PVC and CPE roofing membranes and to monitor the surface and the inner temperatures of the applied roof systems.[2] The waterproofing materials applied to the roof of the field station were also weathered artificially in a weatherometer.

To investigate the degradation of the membranes, the new and the weathered specimens were subjected to various tests. The tensile/elongation tests and the subsequent results concerning tensile strength, elongation and toughness of the new and the weathered membranes were analyzed and evaluated.[3,4] The objectives of this study were to evaluate the basic properties of these membranes by comparing test results with standards and to understand the level of degradation by comparing test results of the new and the weathered membranes.

DURABILITY OF THE BITUMINOUS AND SYNTHETIC SINGLE-PLY MEMBRANES

The durability of a roofing system or material depends on the interaction of a number of variables such as the types of constituent materials, design, production, installation, physical environment, use, etc.[5]

A weathered bitumen surface is attacked by solar radiation and atmospheric oxygen and gradually degrades and finally fails before the end of its expected life.[6-8] Thermal load influences the mechanical properties, splitting and permeability. The development of brittle fractures through the loss of volatile components, such as bitumen, is also an effective factor.[9] The deterioration is more rapid on roofs with thermal insulation applied immediately beneath the bituminous membrane, where the insulation amplifies the temperature fluctuations. The attack of heat (especially more than 70°C [158°F]), UV radiation and atmospheric oxidation to bitumen membranes generally causes embrittlement, a decrease

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in strength, and low-temperature flexibility and pimpling due to photo oxidation. [10-12]

A majority of the polymer waterproofing membranes is also attacked by solar radiation heat and atmospheric oxygen.[13,14] Consequently, polymer chains may break and relink; oxidative reactions occur; crystal forms of polymer may change; the plasticizer or stabilizer may leach, evaporate or migrate; and the constituent material of the composite may deteriorate. These processes influence a number of mechanical properties and the products gradually degrade. The degradation may take the form of crazing, cracking and embrittlement, which may change the strength, elongation, flexibility, color and the dimensions.

Most polymers absorb infrared radiation from the solar spectrum, with a consequent rise in temperature. Heat plays a part in determining the rate of the chemical reactions leading to the degradation of polymers, such as PVC, which is subject to solar-induced photo oxidative deterioration.[15] Degradation during manufacturing can also increase the light-absorbing capacity of a polymer in the near ultraviolet range, so that it becomes more susceptible to degradation. Ultraviolet radiation with a wavelength between 290 and 380 NM has a sufficient energy intensity to split the polymer chains of plastics. For example, the molecular bonding in PVC membranes can be cracked by absorbed ultraviolet radiation.

Plasticizers may escape from the plasticized polymers by means of evaporation, washout, migration to other substances, and by action of microorganisms. Plasticizers may also escape from the plasticized PVC and cause a change in its mechanical properties. Consequently, the material loses its flexibility, hardens, and its modulus of elasticity increases with considerable shrinkage.[16] A decrease in temperature worsens the state of PVC with insufficient plasticizer creating an additional increase in hardness and shrinkage.

To avoid the degradation caused by the presence of oxygen, heat and ultraviolet radiation, various types of stabilizers and antioxidants are used. The effectiveness of a stabilizer depends on keeping its concentration at the same level in the polymers. However, the concentration of stabilizers in polymers decreases with long-term use.[17] These loses are due either to chemical reactions of the stabilizers or to the physical loss of plasticizers by evaporation, sublimation, extraction, diffusion and/or leaking from polymers.

WEATHERING AND AGING OF ROOFING MATERIALS

To investigate the degradation of the waterproofing materials experimentally, various weathering and testing techniques were developed and applied. The weathering is generally carried out in either a natural environment or in artificial conditions in a laboratory.[18] Field stations, specially designed panels or existing roofs were used for the outdoor weathering of the bituminous as well as the synthetic single-ply membranes in various countries.[19,20] This approach was generally applied to examine the influence of the finish, the slope and the orientations on the surface temperature, and on the degradation of the samples.[1,21,22] The natural weathering results show the real effect of climate. Yet, it is very often difficult to predict the individual effect of each of the climatic factors on the roofing materials or systems.

Field Station Built for Weathering and Temperature Measurement

A field station, in operation from April 1989 to November 1990, was designed for investigating the performance of known roofing systems and materials, as well as to investigate the weathering of waterproofing and thermal insulation materials under the hot-dry climatic conditions of Riyadh. The station consists of five 4.15-m- (13.6-ft-) wide bays. The roof deck is reinforced concrete 120 mm (4.7 in.) thick, with a 1.6 percent slope. To obtain a controlled thermal environment in the building, the external and internal walls and the doors were insulated, and each bay was separately air-conditioned.

Roof Systems and Materials Tested on the Field Station

During the operational phase of the investigation, the roof of the station was divided into three main sections. Each section was further divided into a number of subsections. In the first section, a protected membrane (inverted) roof system was assembled with various thermal insulation materials over waterproofing membranes. See Reference 2 for the application.

The second section was allocated for direct natural weathering of the oxidized and modified bituminous and single-ply PVC and CPE membranes, which were laid out on various thermal insulation materials. A total of 12, black, thick, sand-covered, green and gray chipped, white and aluminum-coated bituminous membranes were applied in the first 12 bays. The applied membranes produced, with either oxidized or atactic polypropylene (APP) modified bitumen matrixes and polyester fiber or glass fiber reinforcement, are the products of three well-known companies. The thickness of the membranes varied between 1.5 and 4.0 mm (0.06 and 0.16 in.). Unreinforced, unreinforced UV-resistant and polyester mesh reinforced plasticized PVC, and polyester mesh reinforced CPE membranes were applied in eight bays. Six bays in this section were exposed to direct solar radiation, while the rest that were roofed with dark and light gray PVC, and with white CPE membranes, were covered with 50-mm- (2-in.-) thick concrete pavers (tiles).

The third section was used to test the warm roof system. The membranes were applied on polyurethane foam boards and expanded polystyrene insulators. They were covered with heavy concrete pavers that had open joints.

Weatherometer and Artificial Weathering

Various artificial weathering devices were used to simulate some of the climatic factors such as heat, humidity, solar radiation and/or near ultraviolet light for aging of the waterproofing membranes. Particular attention has been paid to simulate solar radiation, both ultraviolet (UV) and infrared radiation.[23]

An accelerated weathering tester was used for the artificial weathering of the waterproofing membranes investigated. The tester simulates the effects of solar radiation by means of fluorescent UV lamps, as well as creating an environment with the appropriate heat and condensed water. UV-B lamps with 280 to 315 NM wavelength are used in the weatherometer to cause faster degradation. A controlled condensation system simulates rain, dew or indoor condensation.

The tester had been set for the weathering of the membranes in accordance with the condition: (a) internal air and panel temperature, 70°C (158°F); (b) condensation temperature, from 55°C to 70°C (131°F to 158°F); (c) daily cycle for

UV and condensation, 11/1/11/1 in 24 hours; and (d) duration of UV-B weathering, approximately 2000 hours.

Measured Surface Temperatures of Exposed Materials

The surface temperatures of initially black or dark brown, sand-covered, green and gray chipped, white and aluminum-coated bituminous membranes, as well as dark and light gray plasticized PVC and white elastomer CPE membranes were measured in 20 months. Absolute minimum and maximum and average surface temperatures of all the membranes and the temperatures between the thermal insulation and the membranes in the protected membrane roof systems were presented in Reference 2.

The annual absolute maximum surface temperatures from the white to the black bituminous membranes varied between 57.6°C and 93.5°C (136°F and 200°F). For the same materials but in a different order, the absolute minimum surface temperatures ranged between -7.5°C and -4.7°C (18.5°F and 23.5°F) for the same period, when the ambient temperature was 6.0°C (43°F). The annual difference between the absolute maximum and the absolute minimum surface temperatures, which gave the maximum stress to the surface materials, was 101°C (214°F) for the near black bituminous membrane and 62.5°C (144.5°F) for the white coated membrane. The absolute maximum surface temperatures of the gray chipped bituminous membrane were 78.2°C (173°F) during the summer and 59.4°C (139°F) in the winter periods. For the same material, the absolute minimum surface temperature was -5.5°C (22°F) in the winter period.

The annual absolute maximum surface temperatures from the white CPE and the black extended PU membranes varied between 60.1°C and 95.8°C (140°F and 204°F). For the same materials, but in a different order, the absolute minimum surface temperatures ranged between -8.6°C and -4.0°C (16.5°F and 25°F) for the same period. The annual differences between the surface temperatures were 99.8°C (180°F) for the near black extended PU membrane and 66.5°C (120°F) for the white CPE membrane.

Performance Criteria and Performance Specifications for Roofing

Performance specifications, which state the performance levels required for a type of building or its constituent elements, are not available for all roof systems. The upper and lower limits of appropriate performance criteria have to be established, both for the initial and the lifetime performance of each system.

Mathey's report identifies a specific set of properties, i.e., tensile, flexure, shear, impact and tear strengths, limited creep, pliability, ply adhesion, thermal and moisture expansions act as performance indicators that define the parameters of satisfactory roofing membranes.[24] They were often taken as criteria for evaluating modified bituminous membranes as well as synthetic single-ply membranes.[25, 26] Of the preliminary performance criteria, the tensile strength criterion is considered very important for the ability of the membrane to resist stresses currently in service, such as splitting and blistering.[27] The suggested performance criterion for tensile strength states that the roofing membrane, tested ASTM D 2523,[28] should be able to withstand up to at least 35 kN/m (200 lbf/in.) in the weakest direction without any ruptures.

The strain energy is another important criterion.[29] During the load/strain test, a test force is applied to a material, work is done as the force is increased, and the material specimen elongates; thus, energy is absorbed. The total work is equal to the area under the load/strain curve.[30] A strain energy criterion considers both the tensile strength and extensibility of a material, and is related to the toughness to withstand energy load before rupture.

Tensile/Elongation Tests of Bituminous Membranes

Tensile strength and elongation at break (load/strain) are considered the primary criteria in the analysis of mechanical properties. Three series of specimen testing were performed. They were tested when they were new, after 20 months of exposure to direct solar radiation and after 2000 hours of artificial weathering. They were tested in longitudinal and transverse directions by the same testing method under laboratory conditions in 23±2°C (73±4°F). For each test series, five to seven test specimens were prepared from each direction of each membrane in the size of 25 x 300 mm (1 x 12 in.) and tested with 100 mm/minute (4 in./minute) cross head speed.

ASTM,[31-34] DIN[35-38] and UEAtc [39,40] standard test methods and specifications were used for testing and evaluation. The requirements stated in the standards were considered and the minimum ultimate tensile strength and elongation at break are accepted as the following: (a) 0.400 N/25 mm (90 lbf/in.) and 40 percent, respectively, for non-woven polyester fiber based (APP) modified bituminous membranes, for both longitudinal and transverse direction; (b) 150 N/25 mm (34 lbf/in.) in longitudinal direction and 100 N/25 mm (23 lbf/in.) in transverse direction and 2 percent, respectively, for non-woven glass fiber matte based oxidized bitumen membrane; and (c) from 96 to 192 N/25 mm (22 to 43 lbf/in.) for both directions of the non-woven glass fiber based bitumen membrane.

Test Results of Modified Bituminous Membranes

The average ultimate strengths and the elongation at break of the new, the naturally and the artificially weathered modified bituminous membranes 1, 2, 3, 8, 9, 11, and 12 are presented in Table 1. The strength of all the membranes for the longitudinal direction varied about 400 N/25 mm (90

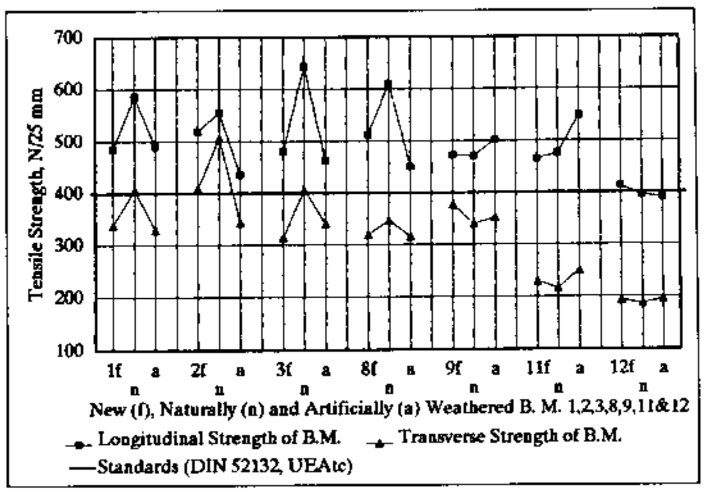

***Figure 1.** Longitudinal and transverse tensile strength of new (f), naturally (n) and artificially (a) weathered APP modified bituminous membranes (B.M.) and standards from DIN 52132 and UEAtc for comparison with.*

Bituminous-(B) and Single-Ply Membranes-(M)	Strength***				Elongation		Force X Elongation			
	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.	Weath/New	
	N/25mm	N/25mm	N/mm	N/mm	%	%	N/mm	N/mm	Long.	Trans.
	k	l	m	n	p	r	m x p	n x r	Ratio	Ratio
1. Fine Sand C. Mo. B. M.										
1f M New	485.0	339.3	19.4	13.6	46.2	55.6	8.96	7.55	1.00	1.00
1n M NW-exposed	585.2	405.6	23.4	16.2	35.6	40.4	8.33	6.55	0.93	0.87
1a M AW-2000 h.	490.0	329.0	19.6	13.2	39.5	39.0	7.74	5.13	0.86	0.68
2. Gray Chip C. Mo. B. M.										
2f M New	519.0	409.0	20.8	16.4	43.2	43.7	8.97	7.15	1.00	1.00
2n M NW-exposed	555.4	507.0	22.2	20.3	32.7	40.2	7.26	8.15	0.81	1.14
2a M AW-2000 h.	436.0	343.0	17.4	13.7	32.6	31.0	5.69	4.26	0.63	0.60
3. Green Chip C. Mo. B. M.										
3f M New	481.2	314.3	19.2	12.6	44.6	47.7	8.58	6.00	1.00	1.00
3n M NW-exposed	642.4	406.6	25.7	16.3	34.0	38.4	8.74	6.25	1.02	1.04
3a M AW-2000 h.	462.5	341.5	18.5	13.7	35.9	38.9	6.64	5.31	0.77	0.89
4. Fine Sand C. Ox. B. M.										
4f O New	259.0	167.6	10.4	6.7	2.87	2.13	0.30	0.14	1.00	1.00
4n O NW-under tile	206.2	177.0	8.2	7.1	2.31	2.00	0.19	0.14	0.64	0.99
4a O AW-2000 h.	235.5	176.5	9.4	7.1	2.10	1.97	0.20	0.14	0.67	0.97
5. Fine Sand C. Ox. B. M.										
5f O New	226.3	183.7	9.1	7.3	2.24	2.22	0.20	0.16	1.00	1.00
5n O NW-under therm.ins.	229.2	208.9	9.2	8.4	2.62	2.35	0.24	0.20	1.18	1.20
5a O AW-2000 h.	246.0	214.5	9.8	8.6	2.35	2.14	0.23	0.18	1.14	1.13
6. Polythene Sheet C. Ox. B. M.										
6f O New	292.9	247.1	11.7	9.9	3.50	2.70	0.41	0.27	1.00	1.00
6n O NW-under prlt tile	302.8	214.8	12.1	8.6	2.69	2.00	0.33	0.17	0.79	0.64
6a O AW-2000 h.	334.0	303.0	13.4	12.1	2.30	2.15	0.31	0.26	0.75	0.98
8. Fine Sand C. Mo. B. M.										
8f M New	512.4	320.1	20.5	12.8	42.70	49.00	8.75	6.27	1.00	1.00
8n M NW-exposed	609.0	346.8	24.4	13.9	30.90	34.80	7.53	4.83	0.86	0.77
8a M AW-2000 h.	450.0	316.5	18.0	12.7	31.50	45.00	5.67	5.70	0.65	0.91
9. Gray Chip C. Mo .B. M.										
9f M New	472.0	377.1	18.9	15.1	36.90	51.30	6.97	7.74	1.00	1.00
9n M NW-exposed	471.6	340.2	18.9	13.6	33.10	37.00	6.24	5.03	0.90	0.65
9a M AW-2000 h.	502.5	352.0	20.1	14.1	29.40	35.80	5.91	5.04	0.85	0.65
11. Fine Sand C. Mo. B. M.										
11f M New	465.0	229.0	18.6	9.2	35.90	71.60	6.68	6.56	1.00	1.00
11n M NW-exposed	475.4	216.0	19.0	8.6	34.50	42.20	6.56	3.65	0.98	0.56
11a M AW-2000 h.	548.5	251.0	21.9	10.0	35.20	56.70	7.72	5.69	1.16	0.87
12. Dark Gray Chip C. Mo. B. M.										
12f M New	412.9	192.9	16.5	7.7	40.50	58.70	6.69	4.53	1.00	1.00
12n M NW-exposed	395.2	187.8	15.8	7.5	38.40	40.00	6.07	3.00	0.91	0.66
12a M AW-2000 h.	391.0	196.0	15.6	7.8	36.20	45.90	5.66	3.60	0.85	0.79
P1 L. Gray PVC M., UnR.	N/mm²	N/mm²								
P1f New	17.1	16.3	25.7	24.5	288.0	328.8	73.96	80.56	1.00	1.00
Pln NW-exposed	16.9	15.9	25.3	23.9	254.7	261.2	64.44	62.32	0.87	0.77
Pla AW-2000 h.	18.8	16.0	28.2	24.0	215.6	175.1	60.73	42.02	0.82	0.52
P2 L. Gray, UV Resistant PVC M., UnR.										
P2f New	19.4	18.2	29.1	27.3	347.1	350.2	101.14	95.43	1.00	1.00
P2n NW-exposed	15.2	14.4	22.9	21.6	242.4	234.3	55.44	50.70	0.55	0.53
P2a AW-2000 h.	17.9	16.2	26.8	24.3	225.4	189.6	60.47	46.13	0.60	0.48
P3 L. Gray PVC M., Reinforced										
P3f New	17.2	13.9	25.8	20.9	24.0	22.8	6.18	4.77	1.00	1.00
P3n NW-exposed	16.7	15.6	25.1	23.5	23.0	25.0	5.77	5.87	0.93	1.23
P3a AW-2000 h.	19.3	17.4	29.0	26.2	23.8	22.8	6.90	5.97	1.12	1.25
P5 White CPE M., Reinforced										
P5f New	31.9	29.1	47.9	43.7	23.1	25.6	11.05	11.17	1.00	1.00
P5n NW-exposed	40.9	27.6	61.4	41.4	17.6	22.4	10.81	9.27	0.98	0.83
P5a AW-2000 h.	30.1	27.8	45.1	41.7	18.7	24.0	8.43	10.02	0.76	0.90

Mo: Modified, Ox: Oxidized, C: Protected, NW: Naturally Weathered, AW: Artificially Weathered, UnR: UnReinforced

***Since the thickness of the bituminous membranes were not considered, for the comparison of the strengths in terms of membrane performance in place, the strengths of the membranes were converted from N/mm² and N/25mm to N/mm.

Table 1: *Average of the longitudinal and transversal tensile/elongation test results of the New-(f), Naturally-(n) and Artificially-(a) weathered modified and oxidized bituminous, and PVC and CPE membranes, and force x elongation of the new and weathered membranes.*

lbf/in.). However, the transverse strength of the same membranes differs greatly and falls as low as 187.8 N/25 mm (42 lbf/in.). (See Figure 1.) The differences between the maximum and the minimum longitudinal strength of the new, the naturally and the artificially weathered membranes are 25 percent, 65 percent and 40 percent, respectively. The differences are much higher for the transverse direction, which are 112 percent, 170 percent and 75 percent, respectively. The differences increase dramatically especially for the naturally weathered materials. The high level of change in the strength shows that the membranes perform considerably differently when in use. It also reflects the significant difference in the quality of the production from one company to another.

The strength of the new membranes in longitudinal direction meets the standard requirements; however, the transverse strengths of most of the membranes are considerably lower than the cross strength to the contrary of the standard requirements. (See Figure 1.) Therefore, the membranes are much more vulnerable in the transverse direction.

The effects of weathering do not exhibit any particular pattern; however, the direct exposure to solar radiation increased the strength of the first four membranes (1, 2, 3, and 8) unlike the strength of the other three (membranes 9, 11, and 12). Artificial weathering creates conditions that are comparatively more severe, and actually decreased the strength of the same membranes. This result indicates that 20 months of natural weathering could be considered mild weathering and in fact increases the strength of the membranes up to a certain point, although the membrane strength is decreased by artificial weathering in severe conditions.

The elongation at the break of most of the new modified bituminous membranes were more than 40 percent in the longitudinal as well as in the transverse direction. The variations in the elongation of the membranes are shown in Figure 2. For all the membranes, the longitudinal elongations are lower than the transverse ones, unlike the strengths of the same materials. The natural and the artificial weathering decreased the elongation of the membranes. However, the decrease in elongation is greater for the naturally weathered membranes. Therefore, the natural weathering had more effect on the elongation of the membranes than artificial weathering.

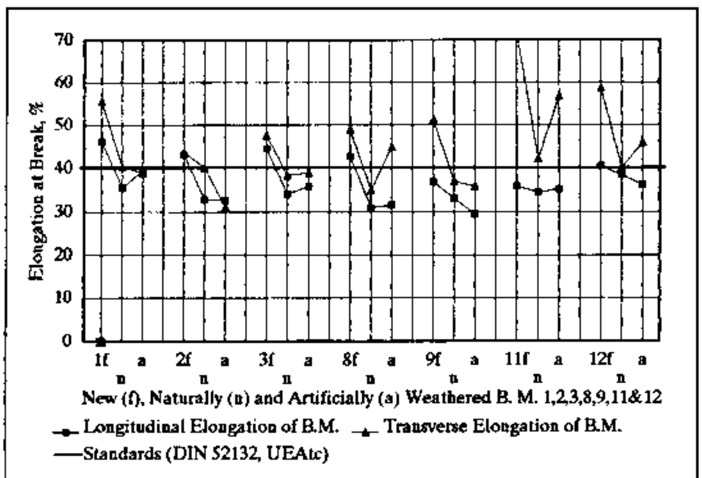

Figure 2. Longitudinal and transverse elongation of new (f), naturally (n) and artificially (a) weathered APP modified bituminous membranes (B.M.) and standards from DIN 52132 and UEAtc for comparison with.

Test Results of Oxidized Bitumen Membranes

The average ultimate tensile strength and the elongation at the break of the new and the weathered glass fiber based oxidized bituminous membranes (4, 5 and 6) are also given in Table 1. The average strength of the new membranes was more than 200 N/25 mm (45 lbf/in.) for the longitudinal direction. However, the variations of the transverse strength of the membranes were so great that they were scattered above and below 200 N/25 mm (45 lbf/in.). Basically, both the longitudinal and the transverse strength of these membranes were increased by the natural weathering and by the severe artificial weathering. The differences in strength increase comparatively more for the artificially weathered specimens. As shown for the modified membranes, the high differences between the strengths indicate that the membranes manufactured by different companies show a divergent performance of strength in use.

The longitudinal strengths of all three membranes meet the requirements stated in DIN 52128 and ASTM D 2178 for the standard ply as well as for the heavy duty ply. In the transverse direction, the strengths of the new and the weathered membranes, which are generally lower than the cross strengths, also meet the standard requirements for the standard ply sheet. However, membranes 4 and 5 do not meet the requirements stated for the heavy duty sheets.

The average elongation of the new and the weathered oxidized membranes varied between 2 percent and 3.5 percent. The elongations were mostly decreased by the weathering except for membrane 4, which was actually increased by natural weathering. All the oxidized membranes elongate at a point above or close to the 2 percent requirement stated in DIN 52128.

The main problem involving the elongation of the membranes is the very large difference between the elongation of the polyester fiber based modified bituminous membranes and the glass fiber based oxidized bituminous membranes, which were approximately 40 percent and 2 percent, respectively. If long-term performance of low-slope roofing is considered, a membrane with 40 percent elongation may not be replaceable by a membrane with 2 percent elongation to meet similar performance requirements.

Toughness of bituminous membranes

The strain energy required to rupture a material relates to its toughness. The toughness represents the ability of a material to resist forces by deformation, thus, absorbing energy before rupture. The strain energy approach was used to evaluate the toughness of the new and the weathered oxidized bituminous and modified bituminous membranes. To evaluate the change in the toughness of the membranes after weathering, the percentage of the retained fractional strain energy of the new membranes (NM) and weathered membranes (WM) were compared. The ratio is expressed as: Force x Elongation of WM/Force x Elongation of NM.

The ultimate tensile strength and the elongation at break of the new, the exposed and the 2000 hours artificially weathered specimens were considered for the calculation of the ratios. The ratios for the modified and the oxidized bituminous membranes are presented in Table 1. The toughness of the modified bituminous membranes was mostly decreased in the longitudinal as well as in the transverse directions as a result of the natural and the artificial weathering. These

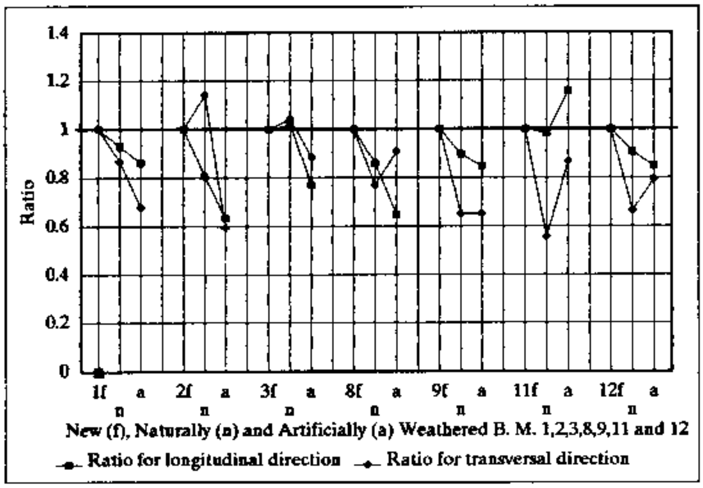

Figure 3. Ratio between longitudinal and transverse force x elongation of the naturally (n) and artificially (a) weathered APP modified bituminous membranes (B.M.) and force x elongation of the same but new (f) APP modified bituminous membranes.

decreases in the toughness vary from 98 percent to 56 percent of the toughness of the new membranes. (See Figure 3.) Overall, these membranes had high strength and high elongation when they were new. Their strength was generally increased, but the elongation was decreased by weathering. Therefore, the toughness of most of the weathered membranes decreased due to a large reduction in their elongation.

The toughness of oxidized membranes 4 and 6 was reduced in most cases in both directions by the natural and the artificial weathering. The decreases varied from 99 percent to 64 percent of the toughness of the new membranes. However the toughness of membrane 5 was boosted to 120 percent to that of the new membrane by both types of weathering. Membranes 4 and 5 are made up of the same constituents and are produced by the same company. It would be normal to expect that they possess the same performance characteristics instead of having a contradictory toughness when they were weathered.

Tensile/elongation tests of polymer membranes

All the PVC and CPE membranes investigated were tested in longitudinal and transverse directions. ASTM D 412, D 638, D 2523 and D 4434 (USA), DIN 16726, DIN 16730, DIN 16734 and DIN 53445 (German), JIS K6301, and A 6008 (Japan) and UEAtc MOAT29 (European) standard test methods and specifications were considered for the testing and evaluation.[41-52] Five to seven test specimens were prepared from each direction of each membrane in a specified dumbbell shape. The parallel portion of each specimen had a 10 mm (0.4 in.) width and 40 mm (1.6 in.) length. They were tested with 200 mm/minute (8 in./minute) cross head speed.

The required minimum ultimate tensile strengths according to JIS vary between 9.8 and 19.6 N/mm² (1421 and 2842 psi) for the plain as well as the reinforced plastic roofing sheets in longitudinal and transverse directions. For the minimum elongation, the standard requirements vary from 200 to 270 percent for the unreinforced membranes and from 10 and 15 percent for the reinforced ones. The requirements stated in the standards were given in Figures 4 and 5.

Test results of plain and UV-resistant unreinforced PVC membranes

The average ultimate tensile strengths and the elongation at fracture of the new, the naturally and the artificially weathered plain (P1) and UV-resistant (P2) unreinforced PVC membranes are presented in Table 1. The strength of these membranes varied between 2204 and 2813 psi (15.2 and 19.4 N/mm²) in the longitudinal direction. For the transverse direction, the strength fell between 2088 and 2639 psi (14.4 and 18.2 N/mm²). The variations presented in Figure 4 show that the membrane strength decreased with mild or short-term weathering and then increased with further weathering.

The average ultimate elongation of the same membranes (in parallel portion of the dumbbell-shaped specimens) varied between 347.1 percent and 215.6 percent in the longitudinal direction and between 350.2 percent and 175.1 percent in the transverse. (See Figure 5.) The elongation of the plain and the UV-resistant unreinforced membranes decreased steadily when duration or intensity of weathering increased. The decrease in the elongation was not slowed down by UV-resistance treatment of the membrane. These results indicate that the plasticizer and the UV stabilizer are not stable in PVC, at least for the tested specimens, during long-term or intense weathering to protect the membrane from aging.

The strength of the plain unreinforced PVC membrane slightly decreased from 17.1 to 16.9 N/mm² (2480 to 2451 psi) in the longitudinal direction and from 16.3 to 15.9 N/mm² (2364 to 2306 psi) in the transverse due to natural

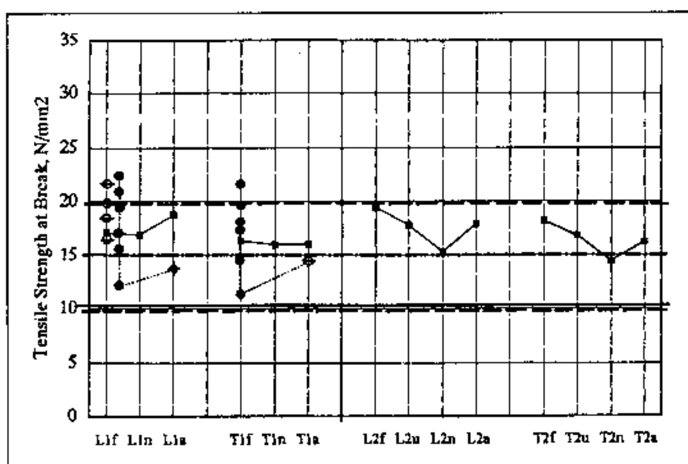

Figure 4. Comparison between longitudinal and transverse tensile strength of new (f), naturally (n) and artificially (a) weathered unreinforced PVC membranes and standard requirements.

weathering and changed to 18.8 and 16.0 N/mm² (2726 and 2320 psi) during 2000 hours artificial weathering. For the UV-resistant membrane, the strength decreased when the membrane was exposed to direct solar radiation, and also when it was protected under concrete pavers. It became 78 percent and 92 percent of the strength of the new membrane in the longitudinal direction and 79 percent and 93 percent in transverse. The strength of the artificially weathered UV-resistant membrane also decreased, but not as much as the strength of the exposed ones. The strength of the new as well as the weathered (plain and UV-resistant) unreinforced PVC membranes meet the standard requirements stated in the related standards, except for one that is specified "excellent" in JIS A6008. (See Figure 4 for the comparison.)

The tensile strengths of the investigated unreinforced PVC membranes were in same range as the tensile strengths measured by Mathey and Rossiter and Laaly and Sereda, which gave the averages of 19.1 and 18.1 N/mm² (2770 and 2625 psi) in longitudinal direction and 16.8 N/mm² (2436 psi) in transverse.[23, 24] (See Figure 4.) They are lower than the strengths of the investigated membranes, however, the results confirm that the strength of the PVC membranes increases after long-term weathering.

The average ultimate elongation of the unreinforced PVC membranes in parallel portion of the specimens were decreased in the longitudinal as well as in transverse directions by the natural and the artificial weathering. (See Figure 5.) The elongation of the plain membrane was decreased from 288 percent to 254.7 percent by natural weathering and to 215.6 percent by artificial weathering in the longitudinal direction. For the transverse direction, the elongation fell from 328.8 percent to 261.2 percent due to natural weathering and to 175.1 percent due to artificial weathering. Thus, the elongation of the weathered specimens became as low as 53 percent of their initial elongation. For the UV-resistant membrane, the elongation of the protected, exposed and artificially weathered specimens decreased as much as 65 percent of the elongation of the new membrane in the longitudinal direction and 54 percent in transverse direction.

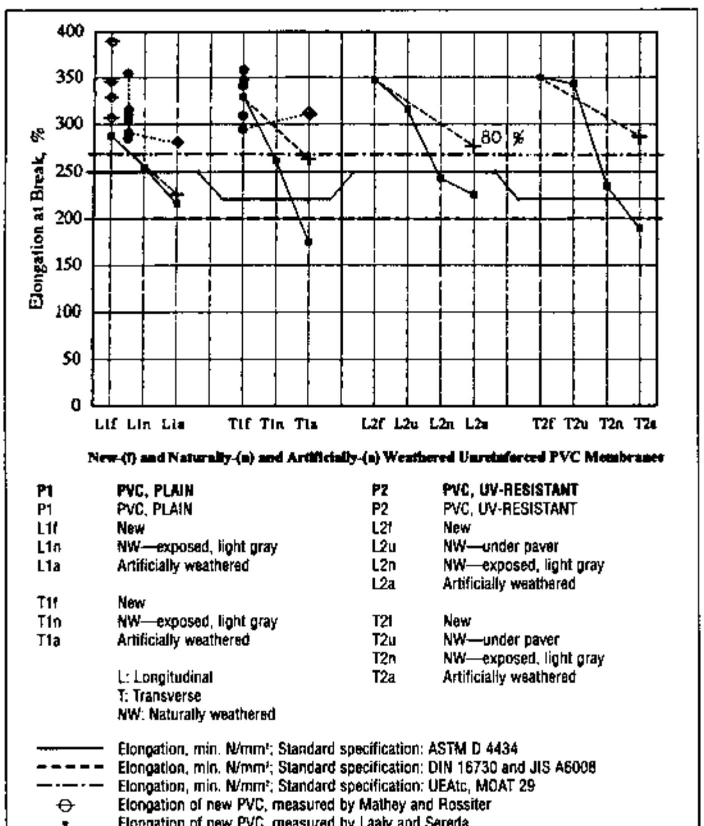

Figure 5. Comparison between longitudinal and transverse elongation of new (f), naturally (n) and artificially (a) weathered unreinforced PVC membranes and standard requirements.

The ultimate elongation of the plain and the UV-resistant unreinforced PVC membranes met the standard requirements when they are new. (See Figure 5.) The UV-resistant membrane also met the requirements after 20 months' weathering in protected condition. As for the exposed membranes, the elongation almost satisfies the requirements. According to the ASTM D 4434, the minimum elongation of a PVC membrane after heat aging has to be at least 80 percent of the new membrane elongation. This requirement is not satisfied by the exposed, as well as by the artificially weathered membranes. (See Figure 5.)

Test results of reinforced PVC and CPE membranes

Tensile/elongation tests of the reinforced PVC (P3) and CPE (P5) membranes were carried out until there was total failure (fracture) of the specimens. The polyester fiber reinforcement contributes to these composite membranes a high modulus of elasticity, strength and stiffness, but low elongation at the yield point. (See Table 1.)

The yield strengths of the new and the weathered reinforced PVC specimens varied between 16.7 and 19.3 N/mm² (2422 and 2799 psi) in the longitudinal direction, and 13.9 and 17.4 N/mm² (2016 and 2523 psi) in the transverse. Therefore, the membrane supports more forces in the longitudinal direction than the transverse. The longitudinal as well as the transverse yield strengths of the membrane meet the specified minimum requirements in the standards and are higher than the strengths of the membranes measured by Mathey and Rossiter. The measured strengths and the standard requirements are compared in Figure 6. The strength of the protected membrane increased to 121 percent and 109 percent of its original strength in the longitudinal and the transverse directions, respectively. For the exposed membrane with a high surface temperature and for the artificially weathered membrane, the strength increased considerably. The increase varied between 13 percent and 26 percent of the initial strength of the membrane. In conclusion, the yield strength of the reinforced PVC membrane is initially increased then decreased by mild weathering; increased again when aging with high temperature and UV by the natural as well as by the artificial weathering.

The elongation of the new and the weathered reinforced PVC membranes at yield point ranged between 23 percent and 24 percent in the longitudinal direction and between 22.8 percent and 25 percent in the transverse. The membrane was tougher and stiffer in the longitudinal direction than the transverse. However, they met the standard requirements in longitudinal as well as in transverse directions. The reinforced PVC membrane weathered with direct solar radiation becomes stronger and stiffer with the same or less elongation. After the fracture of the reinforcement, the speci-

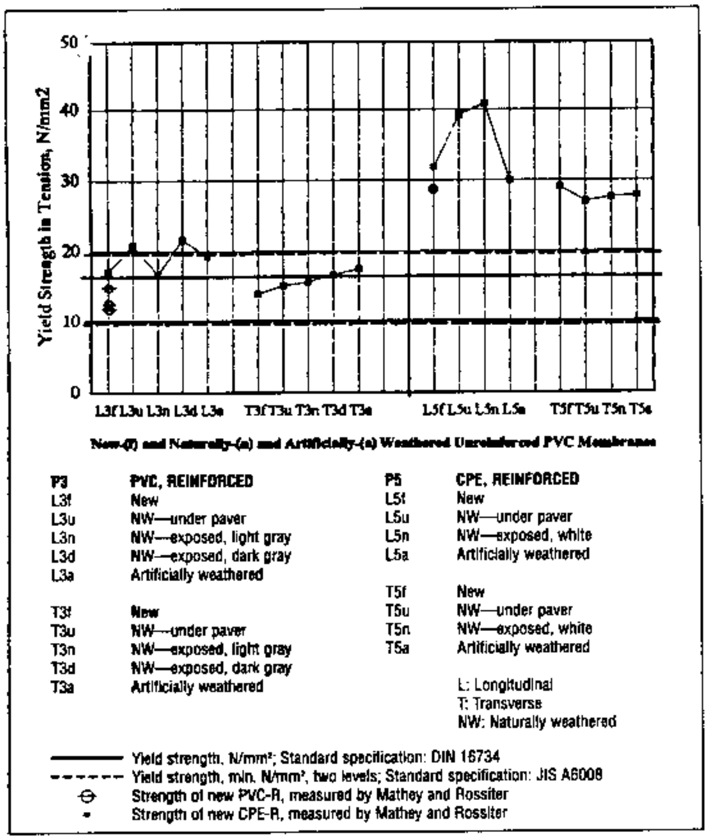

Figure 6. Comparison between longitudinal and transverse yield strengths of new (f), naturally (n) and artificially (a) weathered reinforced PVC and CPE membranes and standard requirements.

mens elongated considerably more. The elongation of the matrix at fracture was 2 to 10 times more than the elongation of the membrane with reinforcement at yield point. These results indicate that the plasticized PVC matrix contributes to the membrane a moderate toughness, low strength, and low stiffness, but high elongation. The matrix was affected much more than the protected polyester reinforcement by the natural and the artificial weathering.

The yield strengths of the new and the weathered CPE specimens varied from 30.1 to 40.9 N/mm² (4365 to 5930 psi) in the longitudinal direction and from 27.6 to 29.1 N/mm² (4002 to 4220 psi) in the transverse. (See Figure 6.) In the longitudinal direction, the yield strength of the membrane as composite considerably increased from 31.9 to 39.2 N/mm² (4625 to 5684 psi) when protected under concrete pavers, and to 40.9 N/mm² (5930 psi) when exposed. But, the strength of the artificially weathered specimen remained at the same level of strength as the new one. Therefore, the strength was gained in a short period of exposure, but was lost with severe weathering, unlike the change in the strength of the PVC membranes. In the transverse direction, the strength of the weathered membrane slightly decreased when compared to the strength of the new one. In both directions, the yield strength of the CPE membrane is considerably higher than the standard requirements. (See Figure 6.)

The new and weathered CPE specimens elongated from 23.1 to 17.6 percent longitudinally and from 22.4 to 25.6 percent transversely. The reinforced CPE membrane was tougher and stiffer in the longitudinal direction than in the transverse. Both the longitudinal and the transverse elongation of the membrane gradually decreased as the weathering was having more and more effect. Thus, the CPE membrane with reinforcement becomes stiffer when weathered.

Toughness of PVC and CPE membranes

The yield strength and the elongation of the new, the exposed and the artificially weathered specimens were considered for the calculation of the toughness ratios. The ratios for the PVC and the CPE membranes are presented in Table 1.

The toughness of the investigated membranes, except the reinforced PVC, were decreased in the longitudinal as well as in the transverse directions as a result of the natural and the artificial weathering. The ratios that show the decrease in toughness vary from 98 percent to 52 percent. The maximum increase in the toughness of the reinforced PVC was 25 percent in the transverse direction when the specimen was artificially weathered. Overall, these membranes had high strength and high elongation when they were new. Their elongation was generally decreased by weathering. Therefore, the toughness of most of the weathered membranes decreased due to a large reduction in their elongation.

COMPARISON OF PVC AND CPE MEMBRANES WITH BITUMINOUS MEMBRANES IN TERMS OF STRENGTH, ELONGATION AND TOUGHNESS

The measured strength and elongation, and the toughness of the polymeric and the bituminous membranes are summarized in Table 1. Since the thicknesses of the membranes were not considered, for the comparison of the strengths in terms of membrane performance in place, the strengths of the membranes were converted from N/mm² and N/25 mm to N/mm.

The strengths of the PVC and the CPE membranes were significantly higher than the strength of the oxidized and the modified bituminous membranes. The difference between the strengths of the new, reinforced PVC membrane and the sand-covered modified bituminous membrane is 32 percent in the longitudinal direction. For the transverse direction, the difference is considerably higher; it reaches up to 92 percent. The highest difference is 147 percent between the strengths of the reinforced CPE membrane and the sand-covered modified bituminous membrane in the transverse direction. The strength of the oxidized bituminous membrane is incompatible with the strength of the other membranes due to the low tensile strength of the glass fiber reinforcement.

The modified bituminous membranes elongate more than the reinforced PVC and CPE membranes, but considerably less than the unreinforced PVC membranes. The elongation of the new modified bituminous membranes is 73 and 157 percent more than the elongation of the reinforced PVC membrane for the longitudinal and the transverse directions, respectively. For the same membrane, the elongation is only 14 and 18 percent of the elongation of the unreinforced PVC membrane for the two directions. The elongation of the oxidized bituminous membrane, approximately 2 percent, is very low when compared with the rest of the tested membranes.

For comparison of the toughness of all the membranes, products of "strength with elongation" are used. (See Figure 7.) The unreinforced PVC membrane is not included in the comparison because it has very high elongation. In general, the membranes are tougher in longitudinal direction than in transverse. The modified bituminous and the PVC membranes are similar in terms of toughness with respect to strain energy. However, the oxidized bitumen membranes have very low toughness and CPE membranes have high toughness. Toughness of all the membranes was decreased by severe weathering, except for the reinforced PVC.

CONCLUDING REMARKS

- The ultimate longitudinal strength of all the new polyester fiber reinforced modified bituminous membranes that were tested meet the standard requirements stated in ASTM D 4434, DIN 52132 and UEAtc MOAT-N.30. Both the natural and the artificial weathering did not reduce their longitudinal strengths to below that of the standard requirements. In the transverse direction, all the new and the weathered modified bituminous membranes failed to meet the standard requirements, except the naturally weathered membrane 1, 2 and 3.

  The ultimate strengths of the unreinforced plain and the UV-resistant PVC membranes that were tested in both the longitudinal and the transverse directions meet all the standard requirements stated in ASTM D 4434, DIN 16730, UEAtc MOAT-N.29 and JIS A6008. But, artificial weathering reduced their respective strengths below that of the standard requirements given in ASTM D 4434 and UEAtc MOAT-N.29.

  The longitudinal and the transverse yield strengths of the new and the weathered reinforced PVC membrane met at least the minimum requirements specified in both ASTM and JIS standards.

- The elongation of the new modified bituminous membranes in longitudinal and in transverse directions meet the standard requirement of 40 percent elongation. Unlike the strength of these membranes, the weathering reduced their longitudinal and the transverse elongation; therefore, the elongation even decreased to lower than 40 percent in the longitudinal direction.

  The ultimate elongation of the unreinforced plain and the UV-resistant PVC membranes in the longitudinal and in the transverse directions met the highest standard requirement of 270 percent elongation, when they were new. The natural and the artificial weathering reduced the longitudinal and the transverse elongation of the membranes. The elongation remained between the standard requirements of 200 and 270 percent in both directions, except the transverse elongation of the UV-resistant PVC membrane. However, the elongation of the most weathered specimens were lower than the 80 percent of the new membrane elongation, contrary to the requirement stated in ASTM D 4434.

  For the new and the weathered PVC and CPE membranes with reinforcement, the elongation at yield point confirmed the elongation specified for the same type of membranes in DIN 16734 and JIS A 6008.

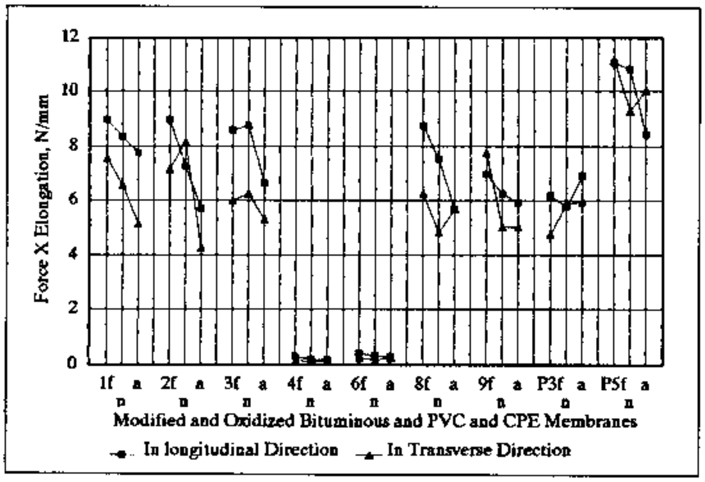

Figure 7. Longitudinal and transverse force x elongation of the new (f), naturally (n) and artificially (a) weathered modified and oxidized bituminous membranes and the new (f), naturally (n) and artificially (a) weathered PVC and CPE membranes.

- The ultimate tensile strengths and elongation of the new and the weathered glass fiber based oxidized bituminous membranes 4, 5 and 6 meet the requirements specified in both DIN and ASTM standards in the longitudinal and the transverse directions, with the exception of the new and the weathered membrane 4. The strength of this membrane did not meet the requirements in the transverse direction.
- The toughness of most modified bituminous membranes, the unreinforced PVC and the reinforced CPE membrane were decreased by weathering due to a large reduction in their prospective elongation. Only the toughness of the reinforced PVC membrane increased by weathering.
- The performance of the investigated modified membranes shows that there is no clear indication to use these membranes on conventional warm roofs where the waterproofing membranes are exposed to the extremes of the hot-dry climate. This is especially so in membranes that are self-finished with mineral chips and are not suitable on the conventional warm roofs where they are directly exposed to solar radiation. Conversely, these membranes are found appropriate for use in protected membrane roofs in a hot-dry climate.
- The UV-resistance treatment did not improve the performance of the PVC membrane in terms of strength and elongation. Both the plain and the UV-resistant membrane should be used in a protected condition rather than be exposed to direct solar radiation. Therefore, there is no advantage to use these membranes in conventional warm roofs where the waterproofing membranes are exposed to the extremes of the hot-dry climate.
- The main problem involving the elongation of the membranes is the very large difference between the elongation of the polyester fiber based modified bituminous membranes and the elongation of the glass fiber based oxidized bitumen membranes. This high difference is supported by the standard requirements that are given as 40 percent and 2 percent, respectively. If 40 percent elongation, which is performed by the polyester fiber based modified bituminous membranes, is found appropriate to fulfill the roofing requirements in terms of the elongation and flexibility, the membrane with 2 percent elongation cannot fulfill the requirement. In conclusion, it would seem that there is justification for an investigation to determine accurate performance criteria for the water-

proofing appropriate for roofing systems.

There is also a significant difference between the elongation of the unreinforced PVC membranes and the elongation of the polyester fiber based PVC and CPE membranes. This difference is also supported by the standard requirements that are given as 200-270 percent and 10-15 percent, respectively. The difference is also significant between the elongation of the bituminous membranes and the elongation of the PVC and the CPE membranes. This supports the requirement for an investigation to determine accurate performance criteria for waterproofing appropriate to design low-slope roof systems.

- Strain energy (toughness or product of strength with elongation), which indicates the mechanical performance of the membranes, could be used as one of the criteria, along with tensile strength/elongation, which could be standardized by roofing system rather than by type of roofing membrane.

REFERENCES

1. Özkan, E., S Al-Deab, and A. R. Al-Tassan. "Investigation of Roofing and Roofing Insulation Materials in the Hot-Dry Climate of Saudi Arabia," Final Report, King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia, 1992, 3.026-3.051.
2. Özkan, E. "Surface and Inner Temperature Attainment of Flat Roof Systems in Hot-Dry Climate," Building Research and Information, Building Research and Information V.21, N.1, England, 1993, 25-35.
3. Özkan, E. "The Strength, Elongation and Toughness of Fresh and Weathered Bituminous Roofing Membranes," pp.226-233, Building Research and Information, Building Research and Information V.21, N.4, England, 1993.
4. Özkan, E. "Strength, Elongation and Toughness of New and Weathered Polyvinyl Chloride and Chlorinated Polyethylene Roofing Membranes," *Architectural Science Review*, V.37, N.3, Sydney, Australia, 1994, 123-135.
5. Cash, C. G. "Durability of Bituminous Built-Up Roofing Membranes, Durability of Building Materials and Components," *Proceedings of the First International Conference*, Sereda P.J., Litvan G.G. (Eds), ASTM, Philadelphia, Pennsylvania, 1980, 741-755.
6. Ransom, W. H. *Building Failures: Diagnosis and Avoidance*, E. and F.N. Spon Ltd., London, England, 1987, 130-144.
7. Hendricks, N. A. "Success and Failure with (APP) Modified Bitumen," *Proceedings of the 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Illinois, USA, 1985, 129-133.
8. BRS Digest 144: Asphalt and Built-Up Felt Roofing, Durability, HMSO, London, England, 1972.
9. Richardson, B. A. *Defects and Deterioration in Buildings*, E. and F.N. Spon Ltd., London, England, 1991, 150-157.
10. Beech, J. C. and M. J. Bond. The Durability of Bituminous Built-Up Flat Roof Membranes, Third International Conference on the Durability of Building Materials and Components Vol. 2, VTT Symposium 49, Technical Research Center of Finland, Espoo, Finland, 1984, 385-389.
11. McKellar, J. F. and N. S. Allen. *Photochemistry of Man Made Polymers*, Applied Science Publishers, London, 1979.
12. Halasz, A. "The Performance Aspects of SBS Modified Asphalt Roofing Membranes," *Proceedings of the 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Illinois, USA,1985, 123-128.
13. Crowder, J. R.. "Some Aspects of the Durability of Plastics in Building," Durability of Building Materials and Components, ASTM STP 691, Sereda P.J., Litvan G.G., Eds., ASTM, Philadelphia, Pennsylvania, 1980, 153-162.
14. BRE Digest 69: Durability and Application of Plastics, Her Magesty Stationary Office, London, 1987.
15. McKellar, J. F. and N. S. Allen. *Photochemistry of Man-Made Polymers*, Applied Science Publishers, London, 1979.
16. Pastuska, G. "Roof Covering Made of PVC Sheeting: The Effect of Plasticizers on Lifetime and Service Performance," *Proceedings of the 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Illinois, USA, 1985, 173-176.
17. Luston, J. *Physical Loss of Stabilizers from Polymers, Developments in Polymer Stabilization-2*, Scott, G., Ed., Applied Science Publishers Ltd., London, England, 1980.
18. Davis, A. *The Weathering of Polymers, Developments of Polymer Degradation-1*, Applied Science Publishers, London, England, 1977, 243-277.
19. Watts, H. "Performance of the Protected Membrane Roof in Australia," *Proceedings of the 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Illinois, USA, 1985, 302-308.
20. Breder, K. "Accelerated and Natural Weathering of Single Layer PVC Roofing Materials," Third International Conference on Durability of Building Materials and Components Vol. 2, VTT Symposium 49, TRCF, Espoo, Finland, 1984, 399-410.
21. Özkan, E. "A Small Scale Experimental Study for Natural Weathering and Testing of Waterproofing Membranes Used for Roofing," *The Proceedings of XIth International Congress*, CIB'89, Paris, France, 1989.
22. Courville, G. E., et al. "Thermal Performance Measurements of Insulated Roof Systems," *Proceedings of the 1985 International Symposium on Roofing Technology*, National Roofing Contractors Association, Rosemont, Illinois, 1985, 150-156.
23. Philips, R. *Sources and Applications of Ultraviolet Radiation*, Academic Press, London, England, 1983, 185-331.
24. Mathey, R. G. and W. C. Cullen. "Preliminary Performance Criteria for Bituminous Membrane Roofing," National Bureau of Standards, Building Science Series 55, Gaithersburg, Maryland, USA, 1974.
25. Mathey, R. G. and W. J. Rossiter, Jr., "A Preliminary Evaluation of the Tensile and Elongation Properties of Single-Ply Sheet Roofing Membrane Materials," *Proceedings of the Second International Conference on the Durability of Building Materials and Components*, National Bureau of Standards, Gaithersburg, Maryland, USA, 1981, 442-451.
26. Laaly, H. O. and P. J. Sereda. "Limitations of Present Test Methods for Roofing Materials, Durability of Building Materials and Components," ASTM STP 691, Sereda, P.J. and Litvan, G.G. Eds., ASTM, Philadelphia, Pennsylvania, USA, 1980, 755-766.

27. Busching, H. M., W. J. Rossiter, Jr. and R. G. Mathey. *Suggested Approaches for Revision of Preliminary Performance Criteria for Tensile and Tensile Fatigue Strength Tests of Bituminous Membrane Roofing,* National Bureau of Standards, NBSIR 86-3347, 1986.
28. ASTM D 2523: Standard Practice for Testing Load-Strain Properties of Roofing Membrane, *Annual Book of ASTM Standards,* V.04.04, Philadelphia, PA, 1987.
29. Rossiter, Jr., W. J. and D. P. Betz. Strain Energy of Bituminous Built-Up Membranes: An Alternative to the Tensile Strength Criterion, National Bureau of Standards, NBSIR 86-3418, Gaithersburg, Maryland, USA, 1986.
30. Timoshenco S. and G. H. Mac Cullough. *Elements of Strength of Materials,* 5th Ed., Van Nostrand Reinhold, New York, 1968, 39-45.
31. ASTM D 146-78a (Reapproved 1986), Standard Methods of Sampling and Testing Bitumen-Saturated Felts and Woven Fabrics for Roofing and Waterproofing, *Annual Book of ASTM Standards,* V.04.04, Philadelphia, Pennsylvania, USA, 1987, 61-68.
32. ASTM D 226-87, Standard Specification For Asphalt-Saturated Organic Felt Used in Roofing and Waterproofing, Ibid, 78-80.
33. ASTM D 1327-86, Standard Specification for Bitumen Saturated Woven Burlap Fabrics Used in Roofing and Waterproofing, Ibid, 144-145.
34. ASTM D 2178-86a, Standard Specification for Asphalt Glass Felt Used in Roofing and Waterproofing, Ibid, 195-197.
35. DIN 52123, Testing Bitumen and Polymer Bitumen Sheeting and Felts, Deutsches Institut fur Normung e.V., Berlin, Germany, 1985.
36. DIN 52128, Bituminous Roof Sheeting with Felt Core, Ibid, 1985.
37. DIN 52130, Bitumen Roofing Felt, Ibid,1985.
38. DIN 52132, Polymer Bitumen Roofing Felt, Ibid, 1985.
39. UEAtc, MOAT N.27, General Directive for the Assessment of Roof Waterproofing System, British Board of Agrément, Watford, UK, 1983.
40. UEAtc, MOAT N.30, Special Directives for the Assessment of Reinforced Waterproofing Coverings in Atactic Polypropylene (APP) Polymer Bitumen, Ibid, 1984.
41. ASTM D 412: Standard Test Methods for Rubber Properties in Tension, Annual Book of ASTM Standards V.08.01, ASTM, Philadelphia, 1987.
42. ASTM D 638M-89, Standard Test Methods for Tensile Properties of Plastics, Ibid, 1989.
43. ASTM D 2523, "Standard Practice for Testing Load-Strain Properties of Roofing Membranes," *Annual Book of ASTM Standards,* V.04.04, ASTM, Philadelphia, Pennsylvania, USA, 1987.
44. ASTM D 4434-85, Standard Specifications for Polyvinyl Chloride Sheet Roofing, 1987.
45. DIN 16726, Plastic Roofing Sheets and Plastic Sheets for Waterproofing; Testing, Deutsches Institut für Normung E. V., Berlin, Germany, 1985.
46. DIN 16730, Plastic Roofing Sheets Made of Plasticized Polyvinyl Chloride (PVC); Incompatible with Bitumen, Ibid, 1985.
47. DIN 16734, Man-Made Fiber Reinforced Plasticized PVC-P Roofing Felt; Incompatible with Bitumen, Ibid, 1986.
48. DIN 53455, Testing of Plastics; Tensile Test, Ibid.
49. JIS K6301, Physical Testing Methods for Vulcanized Rubber, Japanese Standards Association, Tokyo, Japan,1975.
50. JIS A6008, Synthetic Polymeric Roofing Sheets, Ibid, 1986.
51. UEAtc, MOAT N.27, General Directive for the Assessment of Roof Waterproofing System, British Board of Agrément, Watford, UK, 1983.
52. UEAtc, MOAT N.29, Directives for the Assessment of Roofing Systems Using PVC Sheets without Reinforcement, Loose Laid Under Heavy Protection and not Compatible with Bitumen.