

**EVALUATION OF ELASTOMERIC
MEMBRANE SYSTEMS
USED IN PARKING
GARAGE PROTECTION**



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FINAL REPORT

for

Ontario Ministry of Housing
Canadian Institute of Public Real Estate Companies
Canada Mortgage and Housing Corporation
Public Works Canada
National Research Council of Canada

Evaluation of Elastomeric Membrane Systems Used in Parking Garage Protection

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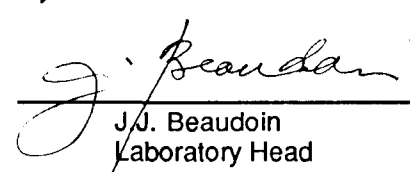

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Report No. CR 6145.3
Report date: 10 February, 1992
Contract No. CR 6145
Reference: Application for test dated 27 March 1990
Laboratory: Materials

93 pages
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**Client Report for
CIPREC/ CMHC/ MOH/ NRC/ PWC**

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ACKNOWLEDGEMENTS

In addition to their financial support, the following organisations contributed considerably to discussions useful to this report: the Canadian Institute of Public Real Estate Companies, the Canadian Mortgage and Housing Corporation, the Ontario Ministry of Housing, and Public Works Canada. We are grateful for their contributions.

We also wish to acknowledge the support of those who provided material for this study. It was their help and cooperation which permitted us to proceed with the work in a timely manner.

The substance of the report owes much to the cooperation of many organisations, companies and individuals who consented to be interviewed and provide information. We are thankful for their participation. We also acknowledge Dr. R. Feldman's critical analysis of some of the technical content of this report.

The report contains a significant contribution from Dr. G. Litvan who, as consultant on the project, undertook a review of the planning and execution of the study. His help is gratefully acknowledged.

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EXECUTIVE SUMMARY

The lack of standards or specifications for parking garage membrane systems creates a problem for potential users as regards selection, application and inspection. Until reliable standards are established, the designer and specifier must evaluate the product by their field history under conditions similar to the job at hand, the relevance of the test data available from product literature, as well as the applied and long-term maintenance cost of these products. This project addresses the issue of the relevance of product test data and provides guidelines for the selection of membranes for use in parking garages.

The project consists of two phases, the first of which is contained in this report. In Phase I, the evaluation of the performance of various membranes to chemical, physical and mechanical factors causing degradation is investigated. Phase II of the project will investigate the effect of application factors and in-service conditions on the durability of these products under field conditions. It will also provide an assessment of the relevance of the current test methods used to evaluate the product's performance in service.

Physicochemical techniques and tests to determine mechanical properties were used to characterize and evaluate the properties of the selected membrane systems. The results obtained to date indicate that the effects of high and cold temperatures and some chemicals encountered in the parking garage environment, significantly affect the performance of the membrane. It is evident that the membranes restrict the ingress of moisture and chloride ions. However, improper surface preparation or membrane application can produce pin holes through the formation of blisters permitting the subsequent permeation of chloride ions.

Most membranes were found to be lacking in their ability to accommodate cyclic movement at low temperatures. Although certain membranes passed the low temperature crack bridging test, results from low temperature tensile tests and dynamic mechanical analysis indicate that their performance should be improved to meet in-service conditions encountered in the parking garage environment.

Although no definite trend was observed in the performance of these membranes, an attempt has been made to rank them based on their relative performance in a series of screening tests. Results show that PDM-6 performed the best, both for indoor and outdoor usage. However, there are constraints in using this system for repair and renovation due to height and design load restrictions. In addition, the heat aging tests performed on these systems indicated a susceptibility to degradation which may limit the long term durability of these systems when used in an outdoor environment. Membrane systems PDM-1 to PDM-4, which are based on urethane resins, show a range of values. However, they have essentially the same performance and are suitable for use in both the

indoor and outdoor environments. Of the six membranes evaluated, PDM-5 fared poorly in comparison to the other membrane systems. However, it is difficult to conclude that any membrane is unsuitable for a given environment in the absence of specific performance limits. Consequently, it is not possible to state with credence that one material should be favoured over another for a given application, until after reliable performance criteria are established.

A review of the test methods has shown that specific minimum values of performance are required for the in-service conditions. In order to establish in-service requirements, and develop specific test and relevant performance limits, the following action should be taken:

- i) conduct round robin testing with appropriate test methods to determine suitable performance limits.
- ii) undertake a more comprehensive review of parking garage membranes including the relevance of current laboratory test methods to evaluate in-service performance and the influence of application factors on the finished product obtained.

The first item is in progress under the auspices of the Canadian Government Standards Board. The second item should be done concurrently to provide valuable feedback on the suitability of the test methods and make the establishment of performance values on these new tests feasible.

The criteria that should be considered and tests to be performed in the evaluation and selection of membranes is described in this report. In absence of appropriate performance limits, these criteria, at best, serve as a screening mechanism. They provide limited assurance that an applied membrane will perform as claimed by the manufacturer.

CR 6145 Évaluation des systèmes de membranes élastomères

RÉSUMÉ

L'absence de normes ou de spécifications sur les systèmes de membranes pour les garages de stationnement couverts cause un problème aux utilisateurs potentiels en ce qui concerne le choix, la pose et l'inspection. D'ici à ce que des normes fiables soient établies, le concepteur ou le responsable du cahier des charges doit évaluer le produit d'après la documentation disponible sur les tests qu'on lui a fait subir, son évolution dans des conditions similaires à celles de l'ouvrage envisagé, ainsi que par rapport aux coûts de pose et d'entretien à long terme de ces produits. Ce projet porte sur la pertinence des résultats de tests appliqués aux produits et fournit des lignes directrices quant au choix d'une membrane pour stationnement couvert.

Le projet comporte deux phases, dont la première se trouve décrite ici. Dans un premier temps, nous examinerons l'évaluation des réactions de diverses membranes aux agents chimiques, physiques et mécaniques causant la dégradation. Ensuite, on étudiera l'effet de divers agents d'application et des méthodes d'entretien sur la durabilité de ces produits en situation réelle. On déterminera également si les méthodes habituelles de test évaluent adéquatement la performance du produit à l'usage.

Les caractéristiques des systèmes de membranes choisis ont été déterminées et évaluées à la suite de tests et de techniques physicochimiques propres à en établir les propriétés mécaniques. Les résultats obtenus à ce jour révèlent que la chaleur élevée et le froid, de même que certains produits chimiques dans l'environnement du stationnement affectent sérieusement la performance de la membrane. Bien sûr, elles restreignent l'intrusion de l'humidité et des ions de chlore. Toutefois, une mauvaise préparation de la surface ou une application inadéquate de la membrane peuvent avoir comme résultat la formation de cloques, qui engendrent des trous d'épingles, causant l'infiltration par les ions.

On a constaté que la plupart des membranes résistent mal aux variations cycliques à basse température. Quoique certaines passent le test du "pontage" des fissures à basse température, les résultats aux tests d'élasticité aux mêmes températures et l'analyse de la mécanique des mouvements indiquent que leur performance devrait être rehaussée pour répondre aux conditions d'usage prévalant autour des stationnements couverts.

Bien qu'aucune tendance précise de la performance de ces membranes n'ait été observée, on a tenté de les classer en leur imposant une série de tests de sélection. Les résultats indiquent que PDM-6 est le meilleur système, tant à l'intérieur qu'à l'extérieur. Cependant, des restrictions de poids et de hauteur dans le design peuvent restreindre son utilisation en rénovation et en réparation. De plus, les tests sur le vieillissement dû à la chaleur, appliqués à ces systèmes, montrent une prédisposition à la dégradation qui peut limiter leur durabilité à long terme dans un usage extérieur. Les membranes PDM-1 à PDM-4, à base de résine uréthane, ont des qualités variables. Par ailleurs, elles ont sensiblement le même rendement et conviennent à un usage tant intérieur qu'extérieur. Des six membranes évaluées, la PDM-5 fait des joints médiocres en comparaison des autres. Cependant, on peut difficilement conclure qu'une membrane précise est impropre à un environnement donné en l'absence de limites de rendement spécifiques. En conséquence, on ne peut affirmer avec assurance qu'un matériel doit être privilégié pour une application particulière, jusqu'à ce que des critères de performance fiables soient établis.

Une révision des méthodes d'évaluation a montré que des qualités minimales précises de performance sont requises pour les conditions d'utilisation. Pour établir celles-ci, développer des tests spécifiques et déterminer les limites de rendement pertinentes, on devrait prendre les mesures suivantes :

- i) appliquer des tests au hasard à l'aide de méthodes appropriées pour déterminer les limites de performance acceptables;
- ii) entreprendre une révision systématique des membranes pour garages de stationnement couverts, en tenant compte de la pertinence des méthodes courantes d'essai en laboratoire pour évaluer le rendement sur le terrain et l'importance des facteurs d'application sur la qualité du produit fini obtenu.

La première mesure est en cours d'élaboration avec l'appui de l'Office des normes générales du Canada. La deuxième devrait être prise parallèlement pour fournir un feed-back de grande valeur sur la pertinence des méthodes de mesure et rendre faisable l'établissement de valeurs de rendement dans ces nouveaux tests.

Les critères à considérer et les tests à réaliser dans l'évaluation et la sélection des membranes sont décrits dans le rapport. En l'absence de limites de rendement acceptables, ces critères, au mieux, serviront de grille de sélection. Ils apportent une assurance relative que la membrane posée se comportera conformément aux affirmations du manufacturier.



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I. INTRODUCTION

The selection of elastomeric traffic bearing membranes for use in the protection of concrete slabs should be based on both material properties as well as field experience. However, evaluation is difficult due to the lack of standards and specifications, and consensus concerning the tests to be used for the evaluation of performance. Furthermore, the large number of products on the market and the variability of performance, even by materials of the same generic type, make selection difficult. Due to differences in chemical composition, application characteristics and sensitivity to environmental conditions, nominally similar products will give a range of performance values.

In the absence of regulation, current methods of evaluation for the selection of membranes relies heavily on the following:

- a) manufacturers product data sheet;
- b) products market share;
- c) manufacturer's reputation; and
- d) testimonials of users.

The performance of the product is highly dependant on the expertise of the applicator, the care exercised during the membrane installation, and the prevailing ambient conditions. Therefore, the choice of a membrane should be based on proper evaluation of the material properties, the degree of surface preparation required, the sensitivity of the membrane to adverse conditions during installation and the excellence of the manufacturers quality control to ensure product uniformity. Specifications should stipulate that the membranes be installed by a licensed applicator of the manufacturer. The appropriate surface preparation, on-site quality control, mixing and application, should be detailed in the job specifications. At present there is no document to assist the specifier of waterproof membranes. The work presented in this report endeavors to address the methodology of selection and potential problems in the application of the product in the field.

Project work commenced in May 1990. The work done to date and reported here, constitutes Phase I of the project. In this Phase, material properties and some factors affecting the development of these properties were investigated. The work schedule is shown in Figure 1. Phase II will address the issues of:

- i) the sensitivity of the systems performance to application variables and;
- ii) the effectiveness of current membrane repair methods;
- iii) the relevance of current test methods to evaluate the in-service product performance.

II. SELECTION OF MEMBRANES AND METHODS OF TESTING

The preliminary selection was based on the following criteria:

- widely used brands of membranes;
- widely used generic types;
- type of resin vehicle (water or solvent based).

A literature and market survey, in conjunction with discussions with manufacturers' representatives and members of the Canadian General Standards Board were used, to aid the selection of the membranes and compile the relevant test methods. Pertinent literature is provided in the bibliography (page 32).

The following items were used to ascertain the suitability of a targeted membrane and selected test method:

- (a) comprehensive nature of the product literature addressing test and application data;
- (b) degree of detail of application and curing procedures available;
- (c) test methods used for evaluating product performance;
- (d) sample preparation;

The test methods selected for laboratory evaluation are presented in Table 1.

III. MATERIALS

The designation, type and manufacturer of the six elastomeric membrane systems being evaluated are given below. All systems are liquid applied; no prefabricated sheet materials were investigated.

PDM 1	Urethane (two component, solvent borne); Tremco
PDM 2	Urethane (two component, solvent borne); H. S. Petersen
PDM 3	Urethane (one component);Mameco
PDM 4	Epoxy-Urethane (two component, solvent borne); Sternson
PDM 5	Neoprene (one component, water borne); Master Builders
PDM 6	Rubberized Asphaltic Mastic; Duron

IV. PRODUCT SAMPLING AND PREPARATION OF TEST SPECIMENS

Materials were selected at random from the manufacturers warehouse. For each type of membrane system, two five gallon containers were taken and their batch numbers noted.

Two types of specimens were tested:

- i) free film coupons of the membrane;
- ii) composite membrane samples applied to concrete substrates.

The free film coupons were either dumbbell or rectangular shaped 152 mm x 25 mm (6" x 1") sized specimens. The average thicknesses of the free film membranes are given in Appendix F, Table F20.

Composite membrane/concrete specimens were of 3 types:

- i) 305 mm x 305 mm x 76 mm (12" x 12" x 3") slabs;
- ii) 76 mm x 76 mm x 305 mm (3" x 3" x 12") prisms;
- iii) 102 mm (4") diameter and 152 mm (6") diameter cylinders.

Typical examples of these specimens are shown in Appendix C, Figure C1.

With the exception of the rubberized asphalt mastic, the specimens exposed to various test conditions were dumbbell specimens and 25 mm x 152 mm (1" x 6") coupons. In the case of the asphalt mastic, a 457 mm (18") square sheet was cast and then exposed to the test conditions. The required dumbbells and coupons were then cut from this sheet.

Table 1	
Test Methods used in the Evaluation of Elastomeric Membrane Systems	
Designation	Title
ASTM C666-A	Resistance to rapid freezing and thawing
ASTM C672	Resistance to scaling by deicing chemicals
ASTM C957	Resistance to UV exposure; crack bridging
ASTM D412	Tensile properties of elastomeric membranes
ASTM D471	Resistance to aggressive liquids
ASTM D573	Resistance to heat aging
ASTM D3029	Puncture resistance
ASTM D4060	Abrasion resistance
ASTM D4541	Adhesion to concrete by tensile pull-off
ASTM E96	Water vapour transmission
AASHTO T277-831	Determination of chloride permeability
CGSB 37.58M	Recovery from elongation

The concrete specimens, used as substrates for the various membranes, were cast according to ASTM specifications, following procedures outlined in specific tests. They were cured for periods exceeding 28 days prior to application of the membrane. Specimen types were determined according to specifications outlined in the respective test methods. With the exception of PDM-6 specimens, which were cast by the manufacturer, all samples were prepared in the laboratory. All samples were applied according to manufacturers specifications and after consulting with a representative of the manufacturer.

V. TESTING

The properties evaluated and the test methods used are described below.

A. Free Film Specimens

- (1) *Direct Tensile Strength and Elongation at Break (ASTM D412)*: The tensile strength and percent elongation of control samples (5 specimens were used to obtain average value) were first determined and comparison with the values obtained from test samples was made (see Table 2). In all cases, these properties were determined on the membrane only; no top wear course was included. All samples were cured for 28 days at standard conditions (22°C and 50% relative humidity) prior to testing.
- (2) *Resistance to Heat Aging (ASTM D573)*: The test used to determine resistance to heat aging of rubberized roofing was used instead of the method stipulated for membranes. The latter test method (ASTM C973) subjects a specimen to heat aging after only 24 hours of cure, hence the cure is completed under accelerated conditions in the aging oven, leading to polymeric structures which may or may not correspond to that which occurs in-situ. In order to avoid this uncertainty, testing was carried out according to ASTM method D573 in which specimens are cured at standard conditions 28 days prior to heat aging. Samples were cut from the cured sheets and thereafter exposed to elevated temperatures for various periods of time; in this case, exposure to 40°C and 100°C for 7 and 28 days respectively. After the exposure period, the samples were tested for retention of properties (tensile strength, elongation, weight and length change).
- (3) *Resistance to Automotive Chemicals (ASTM D471)*: Samples were cut from sheets of the free film after curing for 28 days at standard conditions. Changes in tensile strength and elongation were determined after 7 days continuous immersion to various automotive chemicals. Dimensional and weight changes were also monitored weekly for a period of one month.
- (4) *Resistance to UV Exposure (ASTM C957)*: Samples were cured at standard conditions for 28 days prior to exposure to UV radiation. The period of exposure was doubled (to 1000 hours) over that stipulated in ASTM C957. The changes in properties were

determined by mechanical testing, Fourier Transform Infra-Red (FTIR) spectroscopy and Dynamic Mechanical Analysis (DMA).

- (5) *Water Vapour Transmission (ASTM E96)*: After curing for 28 days at room temperature and 50% relative humidity the water vapour transmission and membrane permeance were assessed using the wet cup method.
- (6) *Abrasion Resistance (ASTM D4060)*: Samples were tested with a Taber abrader using CS-17 wheels, loaded with 1000g per arm and run for 3000 cycles. The weight loss was monitored every 1000 cycles and the depth of abrasion measured at the end of the test. Since PDM-5 was not abraded when tested as above, a second series of tests were performed with H-10 wheels, loaded to 1000g per arm and run for 2000 cycles. Again, the weight loss and depth of abrasion were measured.
- (7) *Cold Temperature Properties (ASTM D412)*: The tensile strength and elongation properties were determined at successively lower temperatures : 0°C, -20°C and -40°C. In all cases the membranes were cured for 28 days at standard conditions (22°C, 50% RH) and then exposed to low temperatures in an environmental chamber for 24 hours prior to testing. These values were then compared to reference values.
- (8) *Recovery from Elongation (CGSB-37.58M)*: After curing for 28 days, dumbbell specimens were cut, placed in an expansion jig, then elongated to 100% and held in that position for 1 hour. After this period, the samples were released from stress and allowed to recover. The extent of recovery was determined 15 minutes after the release by direct length comparisons.

B. Composite Membrane Specimens Applied to Concrete Substrates

- (1) *Water Vapour Transmission (ASTM E96)*: The test provides two basic methods simulating variation in service conditions for the measurement of permeance:
 - (a) One side wetted and the other side at 50% humidity;
 - (b) One side exposed to high humidity and the opposing face to low humidity.Method (a) was selected since it approaches more closely the conditions of in-service use of a parking garage membrane. In this method the specimen is placed over a vessel containing distilled water and the assembly is sealed with an elastomeric sealant. The rate of water vapour transmission through the specimen was determined by periodic weighing.
- (2) *Resistance to Rapid Freezing and Thawing (ASTM C666 – method A)*: This method was used to determine the resistance of concrete specimens coated with full membrane systems to repeated cycles of freezing and thawing in water. The 28 day cured specimens (coated prisms with ends sealed with epoxy coating) were cycled between a temperature of -17.8°C and +4.4°C. At intervals not exceeding 36 cycles, the specimens

were removed from the apparatus and their change in length measured. The test was run for 100 cycles.

- (3) *Scaling Test (ASTM C672)*: This test method determines the resistance to scaling of coated horizontal concrete surface exposed to freezing and thawing cycles in the presence of deicing chemicals. It is intended for use in evaluating quantitatively the surface resistance of coated concrete by determining the dry mass of the flaked off material and qualitatively by visual examination.

Twenty-eight day cured concrete specimens of dimensions 305mm x 305mm x 76mm (12" x 12" x 3") were fitted with a dike so that the test surface could be covered with a 3% sodium chloride solution (by weight) to a depth of approximately 6 mm. The specimens were then exposed to 50 freeze-thaw cycles.

After every 5 cycles, the salt solution together with the flaked off material is removed and placed in a watertight container. Each specimen was then washed, returned to the apparatus and covered with a fresh solution of sodium chloride.

- (4) *Determination of Chloride Permeability (AASHTO T277-831)*: The method covers the determination of the permeability of concrete to chloride ions and consists of monitoring the electrical current which passes through a 50 mm (2 in.) long concrete core having a 95 mm (3.75") diameter. A potential difference of 60V DC is maintained for 6 hours across the ends of the core, the ends acting as the anode and cathode respectively. The anodic face is exposed to a 3% NaCl solution (by weight) whereas the cathodic face is exposed to a 0.3% NaOH solution (by weight). The total charge passed, in coulombs, is related to chloride permeability.

- (5) *Adhesion of Membrane to Concrete (ASTM D4541)*: A pneumatic adhesion tester was used to determine the strength of adhesion and the mode of failure of membrane samples applied to the surface of concrete substrates. The specimens were cured for 28 days prior to testing. Only membranes and primers were evaluated. Testing of the entire system could not be performed in a meaningful way because of the many interfaces.

- (6) *Crack Bridging (ASTM C957)*: Composite specimens were subjected to 10 cycles of extension and retraction (maximum opening, 1.6 mm) at a temperature of -26°C. Concrete substrates with varying water/cement ratios and degrees of air entrainment were used instead of cement/asbestos board, as specified by the standard. After applying the membranes to the concrete substrates, the assemblies were cured for 14 days at standard conditions followed by 7 days at 70°C before testing.

VI. RESULTS AND DISCUSSION

The averages values of the results obtained are presented in tables in the text. The individual values of the respective tests are given in Appendix F.

A. Free Film Specimens

(1) *Resistance to Heat Aging:*

The results are presented in Tables 3a to 3d and in Appendix B, Figures B1 and B2 and the values are an average of obtained by testing four (4) specimens. The results in Tables 3a and 3b are presented both in absolute terms and as a percentage of the original unexposed value given in Table 2. Since there is such a wide variation between the mechanical properties of the various membranes, the effects of long term heat aging are compared on the basis of the degree to which a particular property is retained, and is expressed as the percentage (%) retained.

The effects of heat aging have been determined over a range of temperatures (room temperature, increase to 100°C) to reflect conditions attained on an exposed structure under moderate and rigorous ambient conditions.

Table 2 Tensile Strength and Elongation of Free Film Specimens			
Membrane System	Tensile Strength (MPa)	Elongation (%)	Recovery from Elongation (%)
PDM1	22.7	300	87.1
PDM2	3.2	370	98.5
PDM3	3.0	700	93.7
PDM4	4.8	140	58.0
PDM5	8.6	760	69.4
PDM6	0.18	1070	88.0

The following results were obtained:

- Elongation capability generally decreased with increase in heat aging temperature and duration of exposure.
- Exposure to 40°C produced a moderate but overall decrease in mechanical properties. At 100°C, drastic reduction in the percentage of elongation were observed. The magnitude of these effects increased with the duration of the exposure to the elevated temperature.
- Short term exposure (7 day) to 40°C produces an increase in tensile strength, but this increase in most cases is offset by the reduction in elongation.

Table 3a								
Resistance to Heat Aging, Seven Day Exposure								
System	Exposed to 40°C				Exposed to 100°C			
	Tensile Strength		Elongation		Tensile Strength		Elongation	
	(MPa)	% original	(%)	% original	(MPa)	% original	(%)	% original
PDM1	23.9	105	270	90	20.8	92	246	82
PDM2	4.0	125	370	100	5.6	175	407	110
PDM3	3.6	120	723	103	4.7	157	420	60
PDM4	6.6	137	104	74	5.2	108	4.8	3
PDM5	9.7	113	654	86	14.4	167	550	72
PDM6	0.18	100	765	71	*		*	
* samples melted at this temperature								

- The results obtained for samples PDM-2 are noteworthy in that they retained a significant percentage of their mechanical properties even after 28 days exposure to 40°C or even 100°C temperatures.

Table 3b								
Resistance to Heat Aging, Twenty-eight Day Exposure								
System	Exposed to 40°C				Exposed to 100°C			
	Tensile Strength		Elongation		Tensile Strength		Elongation	
	(MPa)	% original	(%)	% original	(MPa)	% original	(%)	% original
PDM1	23.8	105	240	80	15.9	70	185	62
PDM2	4.3	134	370	100	5.4	169	340	92
PDM3	3.4	113	590	84	3.9	130	315	45
PDM4	6.5	135	84	60	1.6	33	1.4	1
PDM5	9.1	106	604	79	9.7	113	160	21
PDM6	0.16	89	702	66	*		*	
* samples melted at this temperature								

- With the exception of PDM-5 exposed to 100°C, all samples showed a weight loss, indicative of a loss of volatile components. PDM-4 showed a drastic weight loss (Table 3c) indicating a possible loss of plasticiser or tar components in this membrane. PDM-6 melted at exposure to 100°C.
- With the exception of PDM-6, all the membranes showed slight shrinkage (Table 3d) upon exposure to higher temperatures. The amount of shrinkage generally was greater for samples heat aged at higher temperatures. Sample specimens PDM-3 and PDM-4 had larger shrinkage values than the other membranes, both approaching the

Table 3c Resistance to Heat Aging, Weight Changes (%)				
Membrane System	Exposed to 40°C		Exposed to 100°C	
	Seven (7) days	Twenty-eight (28) days	Seven (7) days	Twenty-eight (28) days
PDM 1	-2.1	-1.9	-3.1	-2.6
PDM 2	-0.7	-0.7	-1.2	-1.1
PDM 3	-1.1	-2.5	-4.6	-4.6
PDM 4	-6.0	-8.1	-21.1	-23.9
PDM 5	-0.6	-0.5	1.01	0.91
PDM 6	-0.07	-0.09	*	*
* samples melted at this temperature				

performance limit of 5% as established by CGSB-37.58 (see Appendix A, Comparison of the Requirements of the Relevant Standards).

The retention of mechanical properties after exposure to 100°C is important. Most of the exterior decks of the parking garages attain high surface temperatures in the summer, particularly if the membrane wearing course is black. Furthermore, car tires, depending on the distance travelled, can further increase the surface temperature well in excess of 100°C. Therefore, it is essential that the product used in the field retain its mechanical properties when exposed to such temperatures.

The drastic weight-change seen in PDM-4 (Table 3c) may be due to a loss of the more volatile components such as the plasticiser or tar component of the product. The plasticiser ingredient is usually responsible for the degree of flexibility manifested by the material. Loss of this ingredient would make the material less capable to accommodate low temperature movement. This is reflected also by the decrease of elongation and tensile strength values (Table 3a and 3b) on aging.

Extensibility after heat aging is performed in conformity with ASTM C836 as a measure of crack bridging. The membrane sample is applied on a thin concrete block, cured for 14 days at standard conditions and then aged for 14 days at 70°C. Then the concrete block is fractured along its width and extended to create a gap of 6.4 mm between the adjacent surfaces. If the membrane suffers no tears it is considered to meet the requirements of the standard. It is not reasonable to expect the membranes to pass this test unless it becomes detached from the concrete substrate on extension. Assuming a gap created by the fracture process has a width of 0.1 mm, the extension would require a 640% elongation. According to the results of Table 2 only three of the membranes (PDM-3, PDM-5 and PDM-6) possess elongation of this magnitude

Table 3d Resistance to Heat Aging, Length Changes (%)				
Membrane System	Exposed to 40°C		Exposed to 100°C	
	Seven (7) days	Twenty-eight (28) days	Seven (7) days	Twenty-eight (28) days
PDM 1	-1.0	-0.8	-1.5	-1.3
PDM 2	-0.4	-0.8	-1.4	-1.5
PDM 3	-0.4	-1.3	-1.9	-4.5
PDM 4	-2.7	-3.4	-1.8	-4.0
PDM 5	-0.2	-0.2	-0.4	-0.1
PDM 6	0.2	0.4	*	*
* samples melted at this temperature				

even in unexposed condition. On performing ASTM C836 only PDM-5 passed. In order to establish a useful performance limit membranes should be monitored over a range of temperatures, similar to those that occur in service.

(2) *Effect of Automotive Chemicals on Mechanical Properties:*

The results are presented in Tables 4a to 4d and in Appendix B, Figures B3, B4, B7, B8 and B9. The results in Tables 4a and 4b (average of four specimens) are also presented as a percentage of the retained reference value. ASTM standard C957 requires a retention of tensile strength of at least 70% for specimens immersed in water or ethylene glycol. No requirements for retention of elongation are stipulated. The following observations were made:

- In general, small changes in tensile strength values (Table 4a) were obtained on subjecting specimens to motor oil. Specimens of PDM-6 showed a significant increase in tensile strength after immersion. It is surmised that plasticizing agents have been leached from the membrane. Consequently, the polymer matrix is less plasticized and hence more rigid, producing, characteristically, higher tensile strengths but reduced elongations after the absorption of motor oil.
- The tensile strength of specimens after immersion in ethylene glycol showed large changes (mostly decreases) except for PDM-3, which was unaffected and PDM-6, which showed a slight increase in tensile strength.
- The tensile strength of specimens after immersion in water showed significant reductions with the exception of sample PDM-3, which again was unaffected, and sample PDM-6 which showed an increase in tensile strength.

- After seven days exposure in motor oil, the elongation capacity of the PDM-4 sample was reduced to 68% of the reference value whereas the least significantly affected membrane was the neoprene based specimen (PDM-5) which showed little or change in elongation (98%). Reductions in elongation were also observed for samples PDM-1 (83%) and PDM-6 (74%) whereas increases in elongation were obtained for samples PDM-2 and PDM-3 (114%). In the case of samples immersed in ethylene glycol, insignificant changes in elongation were obtained for samples of PDM-3, PDM-5, PDM-6 (102, 93, and 103% resp.) Changes in elongation for PDM-1 and PDM-2 (148, 147 %), were not as significant as those obtained for sample PDM-4 (239%). Similar trends were observed for samples immersed in water.
- Weight changes ranged from a loss to considerable gain for specimens exposed to ethylene glycol.
- The loss of weight and thickness in sample PDM-4 is drastic.
- PDM-3 was mostly unaffected by exposure to automotive chemicals

Table 4a							
Effects of Automotive Chemicals on Direct Tensile Strength							
Membrane System	Reference (MPa)	Motor Oil		Ethylene Glycol		Water	
		(MPa)	% reference	(MPa)	% reference	(MPa)	% reference
PDM1	24.6	19.9	81	18.7	76	18.2	74
PDM2	3.2	3.3	103	0.9	28	1.0	31
PDM3	3.1	3.4	110	3.1	100	3.2	103
PDM4	4.8	7.0	146	2.7	56	2.2	46
PDM5	8.6	7.5	87	5.5	64	6.4	74
PDM6	0.18	0.05	28	0.2	111	0.22	122

Table 4b							
Effects of Automotive Chemicals on Elongation							
Membrane System	Reference (%)	Motor Oil		Ethylene Glycol		Water	
		(%)	% reference	(%)	% reference	(%)	% reference
PDM1	300	250	83	445	148	370	123
PDM2	360	410	114	530	147	490	136
PDM3	700	800	114	710	102	750	107
PDM4	140	95	68	335	239	260	186
PDM5	760	745	98	710	93	740	106
PDM6	1070	795	74	1100	103	1036	97

Table 4c
Weight Changes on Exposure to Automotive Chemicals (%)

Membrane System	Motor Oil				Ethylene Glycol				Water			
	Exposure Period (Days)				Exposure Period (Days)				Exposure Period (Days)			
	7	14	21	28	7	14	21	28	7	14	21	28
PDM 1	0.16	0.16	-	0.14	2.73	3.38	-	3.71	2.91	3.57	-	4.40
PDM 2	2.66	3.42	3.76	3.82	10.50	12.89	13.61	13.94	8.73	8.71	8.95	9.41
PDM 3	-3.8	-4.29	-4.79	-5.03	1.24	1.01	0.72	0.78	1.88	1.94	1.89	2.16
PDM 4	-13.19	-16.35	-	-18.42	-0.70	-1.84	-	-2.18	2.05	2.47	-	3.31
PDM 5	2.02	2.67	3.20	3.61	5.96	4.99	4.67	4.62	3.24	2.83	2.61	2.19
PDM 6	8.87	12.78	15.61	18.22	0.59	0.77	0.81	0.90	0.44	0.69	0.86	1.01

Table 4d
Thickness Changes on Exposure to Automotive Chemicals (%)

Membrane System	Motor Oil				Ethylene Glycol				Water			
	Exposure Period (Days)				Exposure Period (Days)				Exposure Period (Days)			
	7	14	21	28	7	14	21	28	7	14	21	28
PDM 1	-0.32	1.56	-	2.64	0.65	3.22	-	3.71	2.43	5.37	-	4.05
PDM 2	0.05	-1.56	-1.19	-0.60	-6.48	-1.95	-4.28	-2.34	1.66	2.59	3.48	3.56
PDM 3	-3.92	-6.62	-4.23	-4.1	-0.28	-2.2	-1.87	-2.48	2.66	1.61	2.61	2.4
PDM 4	-3.49	-4.70	-	-6.30	-0.06	-0.92	-	-1.56	1.98	3.10	-	2.92
PDM 5	1.31	1.01	1.62	3.36	4.09	3.68	2.74	2.25	2.91	3.61	5.27	4.83
PDM 6	na	na	na	na	na	na	na	na	na	na	na	na

na: data not available; no accurate value could be determined due to softness of membrane

Only PDM-1, PDM-3 and PDM-6 meet the requirements of ASTM C957 for retention of tensile strength (>70% retention) in both ethylene glycol and water. No definite trends were observed with respect to the effect of automotive chemicals on the tensile behaviour of free film membranes. However, the effects produced by ethylene glycol and the loss of weight in certain samples are of interest. The latter would indicate leaching of certain ingredients from the cured materials, although this is not corroborated by concurrent weight loss in some specimens (e.g. PDM-2 & ethylene glycol exposure). The increase in elongation capability may have resulted from a swelling of the rubber in the membrane.

(3) *Effect of UV Exposure on Tensile Strength and Elongation :*

The effects of UV radiation on the mechanical properties of free-film membrane specimens after 1000 hours exposure in a Q-Panel testing device are given in Tables 5a and 5b. Values for tensile strength and elongation are presented in both absolute terms and as a percentage of the reference value (average of four specimens).

Table 5a						
Effects of UV Exposure(@ 1000 hours) on Mechanical Properties of Free Films						
Membrane System	Tensile Strength			Elongation		
	Reference (MPa)	Exposed		Reference (%)	Exposed	
		(MPa)	% reference		(%)	% reference
PDM1	21.8	17.8	82	250	180	72
PDM2	3.4	2.6	76	355	400	113
PDM3	2.4	2.3	96	700	450	64
PDM4	4.6	6.6	143	140	87	62
PDM5	6.1	6.4	105	500	144	29
PDM6	0.18	0.22	122	1070	765	71

The following observations were made:

- In general, there was a marked reduction in the *elongation capacity* of most membrane films, particularly for the neoprene based film specimens (PDM-5; 29% of reference value). In contrast, PDM-2, a 2-component polyurethane based membrane, exhibited a slight increase (113%) in elongation capacity at failure. This cannot be readily explained, since comparable PUR (polyurethane) based membranes typically lost their capacity to stretch after exposure to UV radiation.
- The change of *tensile strength* of free-film specimens on exposure to UV radiation did not show a definite trend. In general, there was a loss in strength for polyurethane based membranes, and an increase in tensile strength for the tar extended epoxy-urethane (PDM-4) and the asphaltic based (PDM-6) film specimens.

The neoprene specimen (PDM-5) displayed a slight increase in tensile strength in spite of the significant loss in elasticity, as described in the previous paragraph.

In order to determine the ability of the wear course to shield the membrane from UV radiation, samples of five systems (membrane and wear course) were prepared and exposed to UV light for 500 hours. Sample PDM-6 was not included in this test as it was not possible to prepare tensile specimens of the composite system from which comparisons could have been made.

The results, provided in Table 5b, indicate that the loss in tensile strength observed in free-film PUR samples is abated due to the shielding effects of the wear course. Furthermore, although an increase in tensile strength is observed for the epoxy-urethane blend (PDM-4) in the full system, this increase is not as great as that seen in the free-film membrane sample only (e.g. 129% retained, full system vs. 143% retained free-film membrane).

Table 5b						
Effects of UV Exposure (@ 500 hours) on Mechanical Properties of Composite Systems						
Membrane System	Tensile Strength			Elongation		
	Reference (MPa)	Exposed		Reference (%)	Exposed	
		(MPa)	% reference		(%)	% reference
PDM1	5.07	5.05	99	180	154	85
PDM2	2.6	2.4	93	183	169	92
PDM3	1.4	1.5	109	21	29	142
PDM4	1.1	1.5	129	205	131	64
PDM5	2.2	2.1	95	680	757	111
PDM6	*	*	*	*	*	*

The use of an integrated wear course will reduce the elongation of the waterproofing system as a whole. It also is itself subjected to degradation due to exposure to UV radiation. However, the greatest effect that wear course shielding provides to the system is the improvement observed in retention of elongation when compared to the free film. With the exception of the epoxy-urethane blend, which shows no change in retained elongation, all the membranes that originally exhibited a large loss of elongation when exposed to UV radiation retain a significantly higher proportion of their original elongation capability. The neoprene membrane system was found to have the largest increase in retained elongation. Thus, the systems waterproofing character can be maintained for a longer period.

The nature of the degradation process can be evaluated using the FTIR technique which is able to detect changes in chemical linkages between the various components of the polymeric structure. More specifically, the degradation process involves the formation of chemical groups which are indicative of polymer chain-scission (breakdown of polymer structure), crosslinking

(creation of new chemical bonds), oxidation, or a combination of these processes. By identifying the types of radicals present after degradation, in relation to those present in an unweathered sample, it is possible to suggest the mechanisms by which the degradative process occurs.

Results of Fourier Transform Infrared Spectroscopy (FTIR) on free-film specimens exposed to 1000 hours of UV radiation are essentially consistent with those of the mechanical tests (details of FTIR analysis are provided in Appendix D). Polyurethane samples (PDM-1 to PDM-3) underwent oxidative degradation and this could lead to a loss in ductility (i.e. loss in tensile strength and/or loss in elongation capacity). Oxidative degradation causes breakdown of the polymer structure and hence a loss in ductility brought about by a reduced crosslinking density. Further degradation may also be attributed to the combined action of water and UV radiation. There is little evidence of degradation due to UV radiation in the case of sample PDM-4 (coal-tar extended epoxy-urethane) whereas more significant changes were detected for the neoprene based membrane (PDM-5). The degradative process involves crosslinking which embrittles the polymeric structure and consequently there is a noticeable loss in elongation capacity of the membrane (i.e. 29% retention elongation).

Results from the DMA of membrane specimens, given in Appendix E, indicate little or no change in the glass transition temperature of specimens exposed to UV radiation. Although changes in chemical structure were detected using FTIR spectroscopy, the extent of those changes on the bulk polymeric properties could not be readily detected using the DMA technique.

(4) *Water Vapour Transmission:*

The results of water vapour transmission across free-film specimens are presented in Table 6. Results (average of three specimens) are presented in two forms: the water vapour transmission rate (WVT, g/hr·m²), based on the wet cup method; permeance, calculated from the values of the WVT and presented in SI units (ng/s·m²·Pa) as well as in English units (perms). The membrane film having the smallest permeance (ca. 2 ng/s·m²·Pa) is the asphaltic based product, PDM-6, whereas the neoprene (PDM-5) in comparison, has a significantly greater value of permeance (730 ng/s·m²·Pa). Hence, there is a considerable difference in the water vapour transmission rates of the different polymeric based membranes being evaluated in this study. The PUR and tar-extended epoxy urethane based membranes (PDM-1 to PDM-4) have permeance values within the same order of magnitude, ranging from 44 to 148 ng/s·m²·Pa.

(5) *Abrasion Resistance:*

The resistance of free-film membranes to two similar abrading wheels is presented in Table 7. The results (average of two specimens) are given in terms of the wear index and the depth of abrasion. In the former case, abrasion resistance is expressed as the mass in grams of material worn away by the action of a rotating wheel after 1000 cycles. Values presented for the

depth of abrasion are self explanatory and generally correlate well with values obtained for the wear index. The membranes with the lowest wear index and the least abraded depth are the most wear resistant. The CS-17 wheels are normally used to determine the abrasion resistance of polymeric coatings. However in this instance, because of the increased wear resistance of certain membranes, a more abrading wheel, H-10 wheels were used to obtain comparative values.

Table 6 Water Vapour Transmission and Permeance of Free Film Specimens			
Membrane System	WVT (g/h·m ²)	Permeance	
		(ng/s·m ² ·Pa)	(perms)
PDM1	0.288	6.85	1.20
PDM2	0.328	7.88	1.38
PDM3	0.617	14.8	2.59
PDM4	0.183	4.40	0.77
PDM5	3.039	73.0	12.77
PDM6	6.14x10 ⁻⁴	0.179	0.03

The results indicate that the rubberized mastic (PDM-6) is the softest, least resistant material. The neoprene based membrane (PDM-5) is the most resistant to abrasion. Both PDM-1 and PDM-2 (2-component PUR) are relatively resistant in comparison to either PDM-3 (1-component PUR) or the PDM-4 (tar-extended epoxy urethane) membrane. Figures C2 and C3 and Figure C4 in Appendix C show examples of waterproofing membranes after abrading with CS-17 wheels and H-10 wheels, respectively. No examples of PDM-6 are shown as the rubberized mastic was so soft that it was eroded beyond recognition during the test.

Table 7 Abrasion Resistance of Free Film Specimens				
Membrane	CS-17 Wheels		H-10 Wheels	
	Wear Index (g/1000 cycles)	Depth Abraded (mm)	Wear Index (g/1000 cycles)	Depth Abraded (mm)
PDM1	0.037	0.097	0.056	0.097
PDM2	0.011	0.055	0.014	0.060
PDM3	0.878	0.420	1.216	0.490
PDM4	0.282	0.282	0.317	0.305
PDM5	+	+	0.042	0.092
PDM6	*	*	*	*
+ membrane not abraded by this type of wheel				
* membrane too soft for determinations by this method				

These values represent only the waterproofing membranes resistance to abrasion, and it should be noted that the function of the wear course in each waterproofing system is to provide abrasion resistance. However, in situations where the wear course is worn off, the results of abrasion tests give a relative index of the degree to which the waterproofing membrane can be degraded. Thus it indicates which of the systems will require quick repairs to restore the wearing surface so that the waterproofing of the deck is not compromised.

The results clearly indicate that the membranes themselves are compromised by even light vehicular traffic. Thus, the importance of maintaining the integrity of the wearing course under all adverse conditions is critical. Testing of the abrasion resistance of the wearing course as part of the composite system will be carried out in Phase II.

(6) *Recovery from Elongation:*

The values obtained for recovery from elongation in Table 2 (average of four specimens) represents the degree to which the membrane will return to its original dimensions after it has been subjected to a continuous load and deformation. It is essentially a measurement of the degree of resilience of the membrane and is indicative of the stress-relaxation capacity of the polymeric matrix. The requirement for this test is a minimum of 85% recovery after loading and, as seen in Table 2, neither PDM-4 (tar-extended epoxy urethane) nor PDM-5 (neoprene) pass this test.

In these latter systems, it is probable that considerable chain scission occurs during the deformation period. If this is so, then the crosslink density of these systems may not be sufficiently high to maintain an adequate elastic recovery after tensile stretching. Some of the factors which contribute to this type of behaviour include the presence of diluent in the formulation, or the nature of the elastomer matrix.

(7) *Cold Temperature Properties:*

Values for the tensile strength and elongation capacity of free-film specimens evaluated at various temperatures (average of five specimens) are presented in Tables 8a and 8b. Trends derived from these results are depicted in Appendix B, Figures B5 and B6.

In Table 8a the variation in the tensile strength with decreasing temperature are shown and in Table 8b the corresponding changes in elongation are given. Characteristic increases are observed in tensile strength with decreasing temperature (PDM-2) and reductions in the elongation capability are also evident. The onset of the strength increase, however, does vary between the membranes tested and this is indicative of the different glass transition temperatures of the membranes. The decreases of elongation between 0°C and -20°C are very important. The values at -20°C for PDM-1, PDM-4, PDM-5 and PDM-6 are extremely low and represent a considerable decrease from their mechanical properties at room temperature. Such values indicate their inability to accommodate movement in the substrate (which may manifest itself through tearing of the membrane) at low temperatures. Such low temperature embrittlement, will reduce ability of these polymers to withstand static loading and dynamic shock without

cracking. The response of PDM-3, however, is typical of long chain PUR based elastomers which may be formulated to retain their mechanical properties for low temperature applications. The membrane retains a large portion of its elongation capacity, even at a temperature of -40°C , while at the same time posting a very large increase in tensile strength.

Table 8a				
Cold Temperature Properties Tensile Strength (MPa)				
Membrane	Temperature $^{\circ}\text{C}$			
	22	0	-20	-40
PDM1	21.8	19.2	24.8	44.8
PDM2	3.5	20.5	34.2	53.2
PDM3	2.4	2.9	8.4	16.1
PDM4	4.6	7.1	7.5	19.3
PDM5	6.2	9.6	19.2	16.9
PDM6	0.18	0.08	0.19	0.48

Table 8b				
Cold Temperature Properties Elongation (%)				
Membrane	Temperature $^{\circ}\text{C}$			
	22	0	-20	-40
PDM1	250.8	56.45	9.5	3.57
PDM2	353.5	242.7	164.0	5.19
PDM3	603.5	597.6	520.5	262.9
PDM4	141.0	79.03	21.92	2.52
PDM5	500.3	273.2	4.07	2.67
PDM6	1069	369.7	63.9	4.78

The described low temperature tests help establish the performance of the various membranes at cold temperatures. Existing low temperature performance tests deal either with the crack bridging ability (discussed later) or flexibility over a mandrel to determine the existence of cracks. These are pass/fail empirical tests, performed at a single temperature, that do not provide information on changes of the mechanical properties of the materials with decreasing temperature.

The values obtained for the mechanical properties of the various polymeric films above reflect the influence of their respective glass transition temperatures on such properties. At temperatures approaching the glass transition of the polymer, there are marked increases in modulus by, in some cases, two orders of magnitude. This phenomenon is characterized by a significant increase in strength and a corresponding decrease in strain capacity of the polymer. Thus, for a membrane to perform adequately at low temperature, it must retain a fair degree of flexibility to sustain in-service stresses.

B. Composite Samples

(1) *Water Vapour Transmission*: Tests were applied to evaluate the effectiveness of the six different waterproofing membrane systems in reducing the transmission of water vapour through various types of concrete substrates. The results (average of two specimens) are presented in Table 9.

Standard water vapour transmission tests (ASTM E96) were conducted on a series of coated and uncoated (control) concrete substrates which were cast at two different water/cement (w/c) ratios (0.45 and 0.55) with, and without air entrainment. Complete systems consisting of both a membrane and a top coat were used. The porosity of concrete varied according to the water/cement ratio and the degree of air entrainment. Several types of concrete were used to investigate the effects of concrete surface parameters on the film formation of the membrane as well as the permeation of water vapour through the porous concrete substrate when used with a waterproofing membrane.

The permeance was calculated for both coated and uncoated specimens based on the quantity of water absorbed through a thin disk (6.9 mm; 0.25") of concrete over a given period of time.

Table 9								
Permeance of Coated and Uncoated Concrete Specimens								
Membrane System	w/c=0.45 non-air entrained		w/c=0.45 air entrained		w/c=0.55 non-air entrained		w/c=0.55 air entrained	
	ng/s·m ² ·Pa	perms	ng/s·m ² ·Pa	perms	ng/s·m ² ·Pa	perms	ng/s·m ² ·Pa	perms
Control	20.5	3.587	31.1	5.442	31.4	5.504	44.1	7.717
PDM1	4.51	0.790	5.98	1.047	6.82	1.193	7.11	1.245
PDM2	4.02	0.704	2.50	0.438	3.78	0.661	2.26	0.395
PDM3	3.24	0.567	3.53	0.618	3.29	0.575	3.34	0.584
PDM4	1.27	0.223	0.93	0.163	1.28	0.224	1.03	0.180
PDM5	2.17	0.380	2.45	0.429	3.14	0.549	1.81	0.318
PDM6*	1.86	0.326	2.75	0.481	2.50	0.438	4.41	0.695
* for membrane only; complete system showed zero water vapour transmission								

Results for "control" specimens show the water vapour transmission through the different types of bare concrete; concretes having lower w/c ratios and a corresponding reduced porosity have lower permeance values whereas higher permeance is obtained in the case where the pore volume and pore structure is changed by an increase in the w/c ratio and by air entrainment. The application of a waterproofing membrane system, in all cases, reduces the permeance of the concrete specimens regardless of the porosity of the concrete. However, the degree to which the

permeance is reduced is dependant on the type of membrane applied to the substrate. This is discussed below.

Although overall permeance is reduced, the PDM-1 system behaves as does the control specimens, e.g. the permeance increases with water/cement ratio and amount of air entrainment. Thus, it appears that the nature of the substrate exerts an influence on the permeance of the membrane as well.

For the PDM-2 system applied to the concrete substrate, there is a reduced permeance found for air-entrained specimens and specimens having higher water/cement ratios, in contrast to that found for control specimens. The effect of the change in water/cement ratio and air entrainment was not obvious.

For the PDM-3 system, the degree of reduction in permeance is essentially the same, independent of the water/cement ratio and the degree of air entrainment.

For the PDM-4 system, the reduction in permeance appears independent of water/cement ratio. It is also, however, lower for concretes with air entrainment than without.

The permeance of the PDM-5 system increases with both water/cement ratio and degree of air entrainment, although this increase is not as great as that for PDM-1.

The values listed in Table 9 for PDM-6 represent the rubberized mastic membrane only. The complete system showed no decrease in weight when tested. This resulted in a water vapour transmission rate too small to accurately calculate and hence a permeability approaching zero. The membrane, however, responds in an identical manner to the control concretes. These results appear to be unusually high. This can be attributed to the presence of numerous pinholes in the membrane that would allow for a greater transmission of water vapour.

It is also evident that the application of a waterproofing membrane system of any type tested to the surface of a concrete substrate significantly reduces the quantity of water vapour transmission through concrete specimens.

The performance of the free film membranes and the composite systems can be compared (Table 6 and Table 9). In both cases PDM-6 is the least permeable, by a large margin. The permeance of PDM-1 for the free film and the highest value for the composite specimens are essentially the same. In all the other cases the composites show a markedly lower permeance. These decreases are due in part to the use of both primers (where required) and wear courses. Both provide an extra barrier to the passage of water vapour. For PDM-5, this decrease is especially significant. For both PDM-2 and PDM-4 the permeance decreases with a decrease in water/cement ratio and air entrainment. It is possible that this decrease comes from the use of primers for both these systems. With an increase of both water/cement ratio and air entrainment the surface of the concrete becomes more porous. Consequently the primers probably penetrate deeper into the concrete and seal the pores. The end result is that a greater volume of primer is used on these types of surfaces resulting in a greater thickness of an impermeable resin layer than on smoother, more even concrete surfaces. However, it would appear that the nature of concrete surface influences the type of film being formed on the surface.

(2) *Scaling Test:*

No discernable change in the appearance of the samples was observed. Membrane adhesion to the concrete was sound. It appears that the membranes prevent moisture ingress thereby stopping the degradation of the concrete at the concrete / membrane interface and ultimately, the degradation of the coating itself.

(3) *Determination of Chloride Permeability (AASHTO T277-831):*

Results obtained from chloride permeability tests on concrete cores are presented in Tables 10a and 10b (average of two specimens). This test measures the effectiveness of the membrane in reducing chloride permeability based on the total electric charge passed.

Table 10a Chloride Permeability as Determined by the Initial Charge across a Concrete Substrate					
Membrane Type	Spec. No	Initial Charge (Coulombs)			
		w/c = 0.45		w/c = 0.55	
		Non-air entrained	Air entrained	Non-air entrained	Air entrained
Control	1	280	370	580	690
	2	260	400	350	650
PDM-1	1	<1	<1	<1	<1
	2	<1	<1	<1	4
PDM-2	1	<1	<1	Ø	<1
	2	<1	<1	<1	<1
PDM-3	1	20	<1	<1	<1
	2	<1	<1	3	<1
PDM-4	1	Ø	<1	3	Ø
	2	Ø	<1	<1	<1
PDM-5	1	<1	20	<1	25
	1	<1	1	<1	45
PDM-6	1	<1	<1	<1	Ø
	2	Ø	<1	<1	<1

During application of current for extended periods, several effects may occur. It may be difficult to differentiate between the initial current rise due to a permeable membrane (due to pinholes and blisters in the membrane) and that due to electrolysis of the solution, which results in gas evolution. Thus, the total charge passed, which is the cumulative charge over 6 hours,

may partially result from the damage to the membrane incurred during the test. Therefore, the magnitude of the current attained initially may be a more representative parameter for evaluating the resistance to chloride penetration of coatings and membranes using the electrical method.

In Table 10a, permeability to chloride ions is determined by the initial charge, whereas the total charge is used as a basis for comparison for results presented in Table 10b. Results are given in coulombs and are presented as a function of the w/c ratio and the degree of air entrainment of the concrete substrate.

For control specimens, it is evident that the nature of the concrete greatly affects the extent of chloride ion permeability. Increasing w/c ratio and air entrainment increase permeability.

Application of the various membranes to the concrete substrate results in much reduced permeability in all cases, in terms of the charge, either initial or total cumulative.

Table 10b Chloride Permeability as Determined by Total Cumulative Charge Attained across a Concrete Substrate after Six Hours					
Membrane Type	Spec. No	Total Charge (Coulombs)			
		w/c = 0.45		w/c = 0.55	
		Non-air entrained	Air entrained	Non-air entrained	Air entrained
Control	1	4375	7305	11040	10860
	2	3965	8325	6350	11020
PDM-1	1	10	<1	<1	2
	2	10	<1	<1	70
PDM-2	1	2	3	<1	Ø
	2	<1	<1	<1	2
PDM-3	1	428	1	132	18
	2	14	<1	155	30
PDM-4	1	Ø	2	30	Ø
	2	Ø	2	3	<1
PDM-5	1	3	195	3	445
	1	3	75	2	560
PDM-6	1	<1	<1	<1	Ø
	2	Ø	<1	<1	<1

The relative effectiveness of the different membrane systems in restricting chloride ingress could not be readily ascertained from this test. The results show that in general all membranes reduce chloride ingress, as long as they retain their mechanical properties.

(4) *Adhesive Strength to Concrete:*

In Table 11 the tensile strength of the bond of the membrane to the concrete substrate and the mode of failure in tension are given. Control specimens were also tested to determine the strength of the base concrete. With the exception of the non-air entrained concrete substrate having a $w/c=0.55$, the various concrete substrates have the same tensile pull-off strength. Results show that the adhesive strength of the membranes are predominantly less than the tensile strength of the concrete.

The modes of failure are discussed on the basis of the strength of the different components of the system. The cohesive strength of the waterproofing polymer can be stronger or weaker than the cohesive strength of the concrete substrate. If the cohesive strength of the polymer is greater than the tensile strength of the concrete, failure occurs in the substrate. If the polymer has a lower cohesive strength than the tensile strength of concrete, then either of two situations may occur. In the first instance, if the cohesive strength of the polymer is greater than the bond strength, then the failure occurs at the bond line, and is described as an adhesive failure. In the second case, if the cohesive strength of the polymer is less than the bond strength, then failure occurs in the polymer and is described as a cohesive failure of the polymer.

Table 11 Tensile Adhesive Strength of the Concrete/Membrane System (MPa)								
Membrane	w/c=0.45 non-air entrained		w/c=0.45 air entrained		w/c=0.55 non-air entrained		w/c=0.55 air entrained	
	Strength	Failure Mode	Strength	Failure Mode	Strength	Failure Mode	Strength	Failure Mode
PDM1	4.88	coh.	4.27	coh.	3.47	coh.	4.88	coh.
PDM2	2.36	adh2.	1.45	adh2.	2.25	adh2.	1.80	adh2.
PDM3	1.85	adh1.	1.59	adh1.	1.36	adh1.	1.56	adh1.
PDM4	3.82	coh.	3.31	coh.	3.42	coh.	3.16	coh.
PDM5	3.75	adh2.	3.56	adh2.	2.55	adh2.	2.88	adh2.
PDM6	0.26	adh1.	0.26	adh1.	0.14	adh1.	0.11	adh1.
Control	4.88	coh.	4.88	coh.	4.32	coh.	4.88	coh.
coh. cohesive failure in the concrete substrate adh1. adhesive failure at the concrete/membrane interface adh2. adhesive failure at the concrete/primer interface								

Cohesive failure in the polymer was not observed in the tests performed on these membranes. Whereas the mode of failure (as described above) was independent of the type of concrete used as a substrate for the various membranes, the strengths observed at failure did vary with concrete type. These strengths generally decrease with an increase in water/cement ratio or with air entrainment.

(5) *Crack Bridging Ability:*

The results in Table 12 (average of four specimens) indicate whether a membrane failed after 10 cycles of stretching by 1.6 mm over a crack at a temperature of -26°C . In the test PDM-1, PDM-4 and PDM-6 all failed. This is not unexpected since it was shown that these three membranes do not readily accommodate movement at low temperatures (e.g. see Table 8b.). The test does not indicate after which cycle the membrane actually failed, nor at which extension or load. Hence, it is not possible to quantify the performance of the various membranes. The results of this test are also highly dependant upon the thickness of the membrane. Typical examples of crack bridging specimens, as well as the test apparatus, are shown in Appendix C, Figure C6 in which specimens PDM-3 and PDM-4 are shown both before and after testing. The crack bridging ability of PDM-3 here manifests itself by a stress line along the interface whereas PDM-4, which failed the test, shows the ruptured membrane.

Table 12 Crack Bridging Ability				
Membrane	w/c=0.45 air entrained	w/c=0.45 non-air entrained	w/c=0.55 air entrained	w/c=0.55 non-air entrained
PDM-1	fail	fail	fail	fail
PDM-2	pass	pass	pass	pass
PDM-3	pass	pass	pass	pass
PDM-4	fail	fail	fail	fail
PDM-5	pass	pass	pass	pass
PDM-6	fail	fail	fail	fail

(6) *Freeze/Thaw Stability:*

The results in Table 13 show the percentage increase or decrease in length of coated concrete prisms observed after 100 cycles of freezing and thawing. It is generally accepted that increases above 0.1% in length represent the onset of fracturing in mortar specimens. The non-air entrained control sample at both water/cement ratios completely deteriorated before the 100 cycles were complete. Air entrainment improves the concretes durability to freeze/thaw action. Concrete specimens having lower water/cement ratios also have improved resistance to freeze/thaw action.

With the exception of PDM-6, all the membrane systems investigated improve the freeze/thaw durability of air-entrained concretes, whereas for non-air entrained concretes, only PDM-2, PDM-3 and PDM-5 improve the freeze/thaw durability of the concrete substrate indicating that the membranes of the other specimens must have lost their waterproofing quality presumably due to cracking.

Table 13				
Length Change after 100 Freeze/Thaw Cycles(%)				
Membrane System	w/c=0.45		w/c=0.55	
	non-air entrained	air entrained	non-air entrained	air entrained
PDM-1	1.323	0.004	1.047	0.041
PDM-2	0.006	0.003	0.006	0.003
PDM-3	-0.038	-0.023	-0.017	-0.013
PDM-4	0.628	0.010	1.371	0.019
PDM-5	0.017	-0.012	-0.031	-0.018
PDM-6	*	12.721	*	12.712

* sample completely deteriorated

VII. CONCLUSIONS

- (1) Heat aging tests indicated a potential inadequacy of heat stability of some membranes. The loss of material due to high temperatures attained on exposed decks in summer may well influence the capability of the membrane to accommodate movement at low temperatures.
- (2) The swelling and softening effect of ethylene glycol could result in the rupture of the membrane by a shearing action caused when cars brake sharply on such a membrane.
- (3) Based on results of FTIR spectroscopy and DMA of the selected membrane samples, the effects of sustained UV radiation on the unshielded membrane are more clearly understood. Chain scission and embrittlement occurs in a number of the membranes on exposure to UV radiation,. This seriously impairs its long term performance.
- (4) The effect of UV radiation on samples of the membrane should be viewed in the context of the shielding produced by the wearing course. Testing of full systems show that the wearing course acts as a shield, and reduces significantly the damaging effects of UV radiation.
- (5) Water vapour transmission results indicate the ability of the membrane to restrict ingress of moisture into the concrete. However, the porosity and nature of the concrete surface, the use of the primers and wear courses appear to influence waterproofing characteristics of the applied membrane, probably through the quality of the adhesive bond formed.
- (6) Although the results show that membranes restrict the intrusion of moisture and chloride ions into concrete substrates onto which they are applied, the presence of pinholes and blisters may significantly affect the ability of a membrane to inhibit the ingress of chloride ions.
- (7) Scaling of the concrete due to chloride ion permeation and moisture saturation of the substrate does not occur in the presence of the thin adhesive membrane. The asphalt membrane showed some signs of deterioration.
- (8) The low temperature behaviour of most membranes, as measured by crack bridging and low temperature elongation, is poor. With the exception of PDM-2, the membranes showed a marked constraint to accommodate cyclic movement at temperatures of -25°C which is typical of severe winter conditions.
- (9) The porosity and nature of the concrete surface appears to affect the adhesive strength of the membranes. Those membranes that fail adhesively under applied stress show delamination occurring at the concrete/membrane interface or the concrete/primer interface. The former indicates possible lack of wetting of the concrete while the latter shows poor inter-coat adhesion.

VIII. GUIDELINES FOR MEMBRANE SYSTEM SELECTION

A. Selection Criteria

Current methods of selection have their origin in the restoration of roof and bridge decks and although they serve as a valuable guide, the specific service conditions peculiar to the parking decks require more relevant information and procedures. As mentioned previously, until reliable standards are established, the designer and specifier must evaluate a products' field history under conditions similar to the job at hand, the relevance of the test data in the product literature, and the products' applied and long term maintenance cost.

To protect concrete effectively, the waterproofing system (membrane and wear course) must have certain properties. Some of the material properties which are critical to the proper functioning of the system and that should be considered when selecting a membrane system include:

- **Impermeability** The whole system (including seals, curbs and joints) should be impermeable to water under all expected conditions.
- **Adhesion** Good adhesion is a primary requirement that should be satisfied under normal, humid, or any other specific conditions to which the deck will be subjected.
- **Mechanical Properties** The membrane must endure stresses imposed by vehicular traffic without damage. The mechanical properties must remain satisfactory at all temperatures likely to be encountered in the parking deck.
- **Resistance to Tearing at Cracks** The membrane should be able to withstand thermal and traffic loading stresses of the concrete that result in cracks not exceeding 3 mm without tearing. This capability should be retained at least at temperatures of -20°C. Properties such as elongation and membrane thickness play a significant role in this important characteristic.
- **Durability** The materials should show minimal detrimental aging effects, such as increase in brittleness, and should be unaffected by exposure to freeze-thaw cycles, salt spray, and a variety of chemicals encountered in the parking deck environment.
- **Ease of Application** Ease of application of the membrane ensures that the product's design properties are realized in the applied material. Consequently, the waterproofing materials should be tolerant of commonly experienced site conditions, such as small amounts of moisture or dust. Two component materials should be reasonably insensitive to slight variations in mixing ratios, be suitable for application at air-shade temperatures of not less than 4°C, and be able to resist damage during construction work.

The usefulness of such criteria in the selection of membranes is recognized. However, the weight of importance of these properties in a given structure should be considered in the context of its' in-service exposure conditions and the extent of use it is subjected to. For

example, in parking garages for apartments where the aisles are short and the occupancy is low the need for a high abrasion resistant system is less than that of a public parking garage or an office complex where long aisle and greater vehicular traffic produces greater wear of the surface. Also, the requirement for good crack bridging character is less stringent in decks constructed with precast concrete elements than in those constructed of poured concrete. The higher number of joints in the former tend to lessen the amount of cracking due to shrinkage stresses.

Other Factors

Other factors which should be considered in the selection of the membrane system are listed below:

- the degree of structural movement anticipated;
- location of the parking garage: inside or outside, above or below ground;
- anticipated volume of vehicular traffic, i.e., commercial vs. residential parking;
- consideration of live-load capacity and height limitations of the garage;
- the nature and extent of deterioration of the concrete deck;
- installation procedure recommended by the manufacturer;
- compatibility with expansion and contraction joint seals;
- ease of repair of the system and the effectiveness of the bond between the old and the new membranes.

B. Performance Ranking

Using the above series of tests, two methods have been used to rank the performance of the various membranes investigated in this study, as shown in Table 14.

The initial method consists of assigning values in each series of tests which corresponds to the level of performance attained by a given membrane in relation to the other membranes in the test. The highest value (6) was assigned to the best performing membrane system in a particular test series, whereas the least performing system was assigned the lowest value (1). For example, the test for cold temperature tensile strength indicates that the most resistant membrane is PDM-2 and the least resistant, PDM-6. Hence, values of 6 and 1, respectively, were assigned to these systems.

In cases where membranes have equal performance in a given test, the average value is assigned to each system. For example, in the case of the WVT test, in which a low permeance is ranked highest, both PDM-2 and PDM-3 have similar values for permeance. Thus the average of the second and third ranks was assigned to both of these membranes.

In instances where a number of tests were performed in a particular test series, the average of the tests in the series was considered in the total.

Table 14
Ranking of Membranes

Test	PDM1	PDM2	PDM3	PDM4	PDM5	PDM6
Dimensional Change						
7d40°C	2 (1)	3.5 (1)	3.5 (1)	1 (1)	5 (1)	6 (1)
7d100°C	4 (1)	5 (1)	2 (1)	3 (1)	6 (1)	1 (1)
28d40°C	3.5 (1)	3.5 (1)	2 (1)	1 (1)	5 (1)	6 (1)
28d100°C	5 (1)	4 (1)	2 (1)	3 (1)	6 (1)	1 (1)
Water Absorption	3 (1)	1 (1)	5 (0)	4 (1)	2 (0)	6 (1)
Crack Bridging	(0)	(1)	(1)	(0)	(1)	(0)
Cold Temp. tensile strength	5	6	3	2	4	1
elongation	2	5	6	3	1	4
Recovery	3 (1)	6 (1)	5 (1)	1 (0)	2 (0)	4 (1)
Heat Aging*						
7d40°C	2/4	5/5	4/6	6/2	3/3	1/1
7d100°C	2/5	6/6	4/3	3/2	5/4	1/1
28d40°C	2/4	5/6	4/5	6/1	3/3	1/2
28d100°C	3/5	6/6	5/4	2/2	4/3	1/1
UV Exposure tensile strength	2 (1)	1 (0)	3 (1)	6 (1)	4 (1)	5 (1)
elongation	5 (0)	6 (1)	3 (0)	2 (0)	1 (0)	4 (0)
Weight Loss						
7d40°C	2	4	3	1	5	6
7d100°C	4	5	3	2	6	1
28d40°C	3	4	2	1	5	6
28d100°C	4	5	3	2	6	1
Chloride Ion initial	5	4	2	3	1	6
6 hour	4.5	3	2	4.5	1	6
Chemical Resistance						
water	1 (1)	3 (1)	4 (1)	5 (1)	2 (1)	6 (1)
ethylene glycol	4 (1)	1 (0)	5 (1)	2 (0)	3 (0)	6 (1)
WVT membrane system	4	3	2	5	1	6
	1	2.5	2.5	5	4	6
Adhesion	6	3	2	5	4	1
total	57 (9)	61 (9)	57 (9)	54 (7)	48 (7)	65 (9)

*for this section the numbers represent tensile strength/elongation

Using this system of ranking, the total scores indicate the level of performance of the various membrane systems in relation to one another when all the tests are weighted equally. The results so arrived at indicate that PDM-6 is the best performing membrane in the group.

A second method employs only a pass or fail criteria from selected tests; pass is assigned a value of one whereas fail is assigned a null value. No averages were calculated within a test series and only certain tests could be evaluated using this method. Using this method, the least performing membrane systems are identified as PDM-4 and PDM-5. All other membranes scored equally well in comparison. It is evident that using the former system, a more comprehensive evaluation is made, however due consideration should be given to individual results.

IX. QUALITY CONTROL AND PRODUCT UNIFORMITY

The following controls are suggested to ensure product uniformity:

- i) During acceptance tests or on placing the order, the manufacturer should supply a representative material together with a general description of the chemical constituents. An infrared spectrographic trace is usually supplied by the membrane manufacturer.
- ii) Samples should be retained from delivered material.
- iii) During application, sampling of the sprayed film should be carried out by spraying the material on to the sample board. Coupons for tensile and elongation tests should be obtained from these specimens. The results of these tests may be compared with those obtained with the material submitted for acceptance. In this way the quality of the products delivered can be tested together with the efficiency of the mixing and spreading operation.
- iv) Samples should also be cut from selected locations of the applied membrane to verify that specified membrane thickness is achieved.

X. RECOMMENDATIONS FOR FURTHER WORK

A waterproofing membrane system must first be evaluated in terms of its chloride ion permeability and water vapour permeance. Experiments have shown that the transmission of both water vapour and chloride ion are severely retarded by all the membrane systems tested. However, neither standard specifies acceptable limits of retardation. This should be investigated and limits determined. In addition current test methods do not provide a method of evaluating the potential for ingress of liquid water into the concrete deck. Since exclusion of water is an important preventive measure in ensuring the durability of the concrete dek, it is important that a test method be developed to evaluate this property.

Of equal importance is a measurement of adhesion of the membrane to the concrete substrate. Adhesion will be greatly affected by surface preparation and application conditions. Therefore the factors affecting membrane adhesion should be studied and evaluated in greater detail than presented in this report.

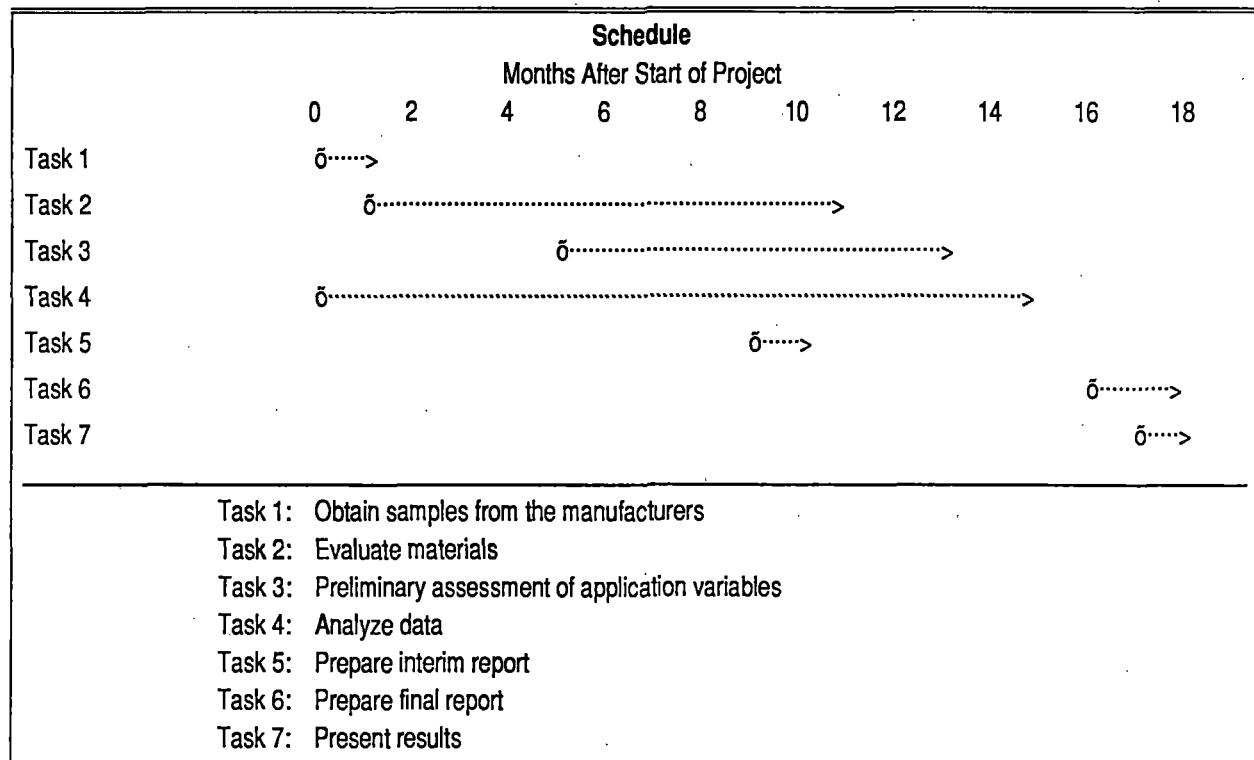
Given that all the membranes do retard chloride ion, water vapour, and adhere well, the performance criteria should then be viewed in terms of the environment in which it is or will be placed. The membrane system must be able to accommodate the changes in environment produced by hot and cold, wet and dry alterations in the weather. The responses to heat aging and cold temperature performance must be evaluated, as well as the effect of chemicals. A concern in the current tests employed is the reliance on data generated from tests performed at one age and one temperature. The resistance to heat aging tests, for example, are performed after 14 days exposure to 70°C. This does not produce enough information to adequately describe the performance of the membrane when exposed to elevated temperatures. A similar case can be made for the cold temperature properties.

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APPENDIX A

Figure A1



Comparison of the Requirements of the Relevant Standards Related to Waterproofing Membranes

Requirements for Elastomeric Cold -Applied Liquid Membranes		CAN/CGSB-37.58 Non-Exposed use in Roofing and Waterproofing	CAN/CGSB-37.59 Exposed use in Roofing	CAN/CGSB-37.60 Exposed Roofing Pedestrian Traffic	ASTM C836 Waterproofing Separate Wear Course	ASTM C957 Waterproofing Integral Wear Course
	Unit	#1	#2	#3	#4	#5
1. Storage Stability	mo	6	6	6	6	6
2. Thickness	mm	1.5	1.5	1.5	1.5	.6
3a) Dimensional Change	%	5				
b) Water Absorption	%	3 in WB 4d at 50°C				
4. Adhesion in Peel	N/m	175 in WB 1d at 50°C	875 as in #1	875 as in #1	175	875
5. Crack Bridging	no crack	Pass/Fail (P/F)	(P/F)	(P/F)	(P/F)	(P/F)
6. Low Temp. Flexibility	no crack	(P/F)	(P/F)	(P/F)	(P/F)	(P/F)
7. Tear Test	N/mm			15		
8. Recovery	%	85 elong. 100%	85 as in #1	85 elong. 50%		90
9. Extensibility after Heat Aging	mm				6.4 no crack	
10. Dynamic Impact	Perf		1 kg falling 10 cm	1 kg falling 25 cm test at 23°C & - 10°C		
11. Static Puncture	Perf		245 N for 30 min.	245 N for 30 min.		
12. Water Tightness	no leak	P/F with 0.5m head for 1d	conditional with items 10 & 11	conditional with items 10 & 11		
13. Sag Flow		0.75mm sag head	0.75mm sag head	0.75mm sag head		
14. Accelerated Weathering			as in #5	as in #5		tensile retention 80% elong. retention 90% after 500 hr
15. Weight Loss	%				20 after 3d at 70°C	40 after 3d at 70°C
16. Chloride Permeability				test required		
17. Abrasion Resistance	mass loss					50 mg
18. Chemical Resistance						tensile retention 70% in water & ethylene glycol, 45 % in mineral spirits

APPENDIX B

Profile of Trends

Figure B1
Resistance to Heat Aging, Weight Changes (%)

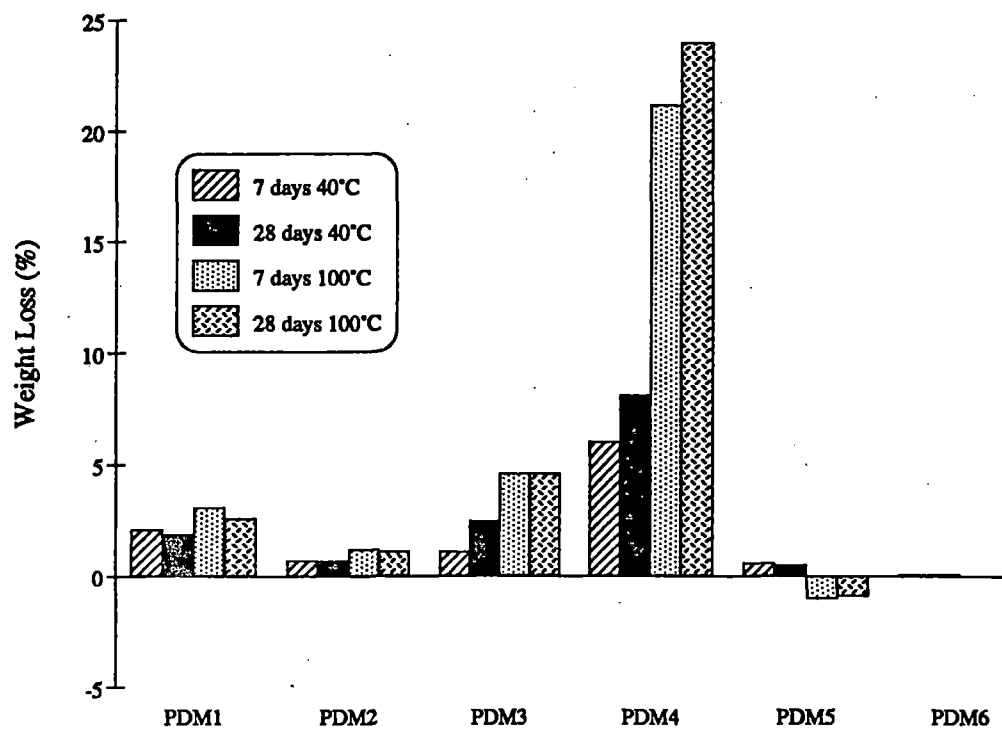


Figure B2
Resistance to Heat Aging, Length Changes (%)

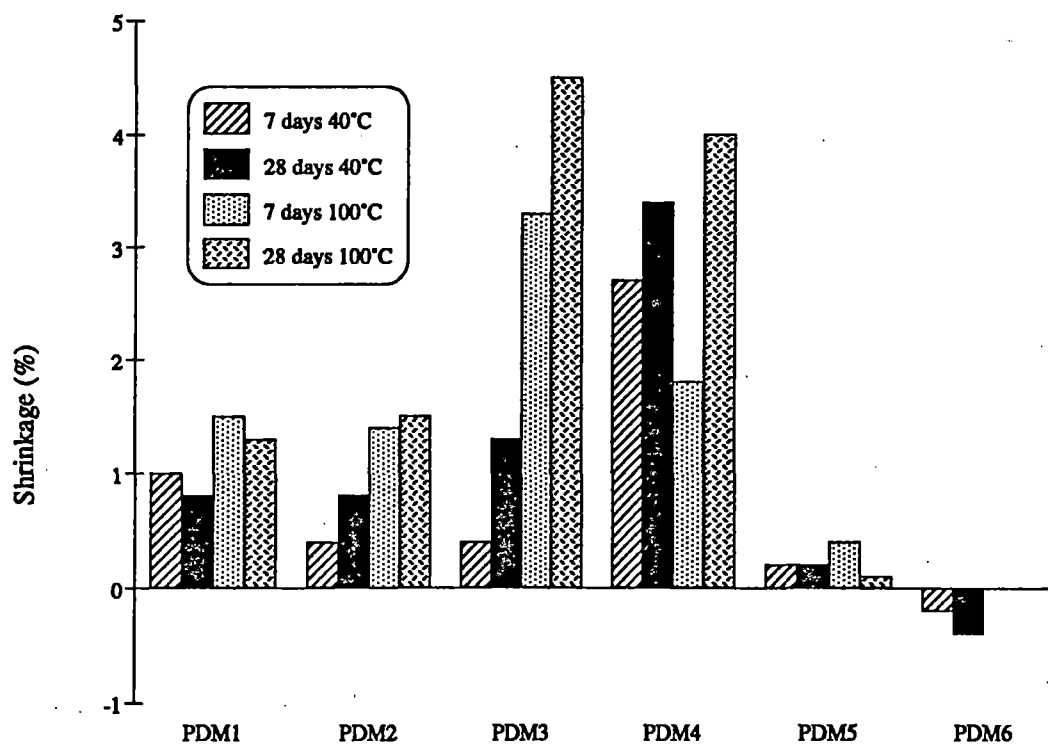


Figure B3
Effect of Automotive Chemicals on Tensile Strength

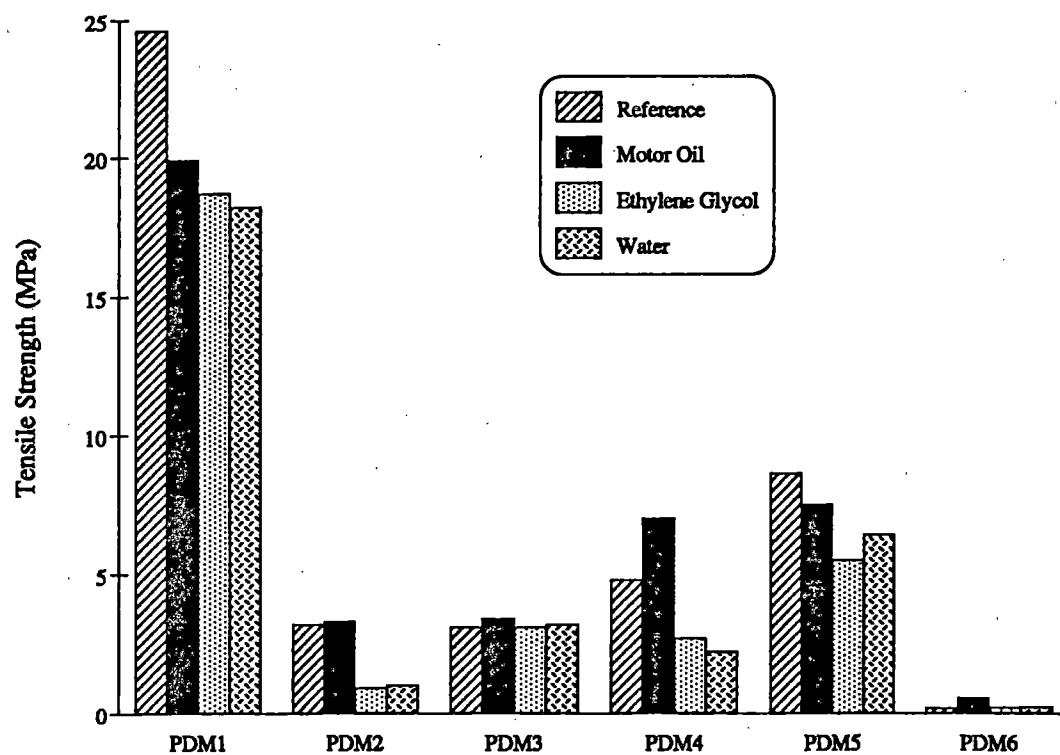


Figure B4
Effect of Automotive Chemicals on Elongation

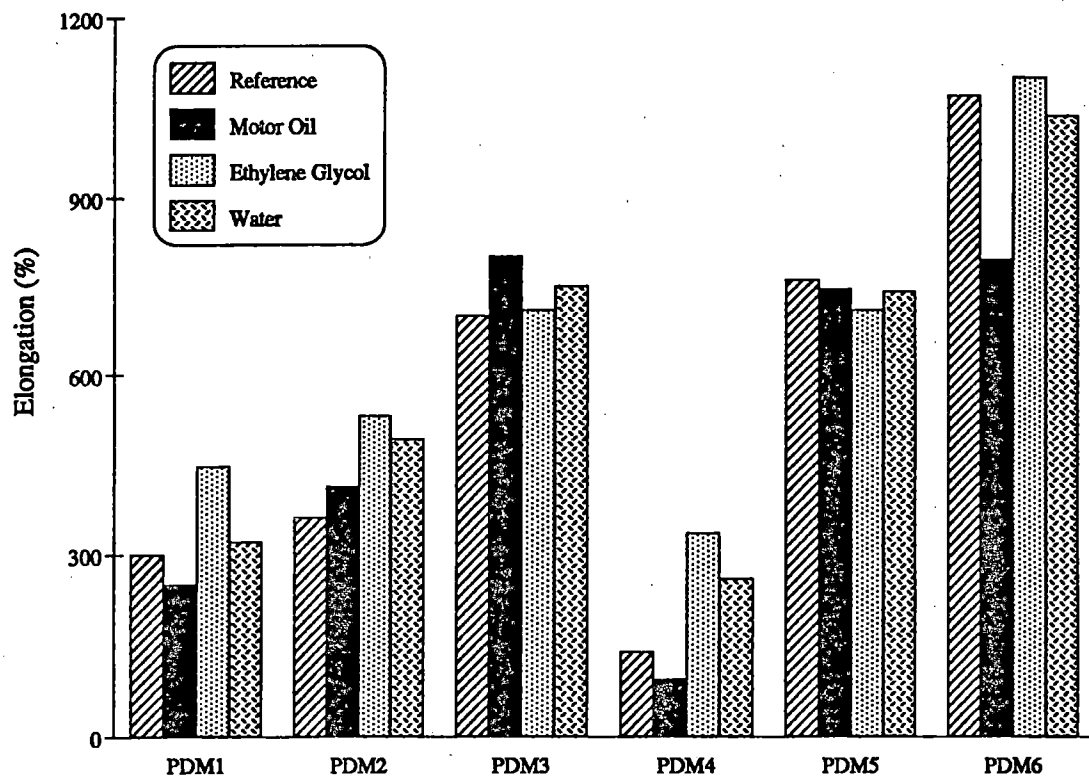


Figure B5

Effect of Cold Temperature on Tensile Strength

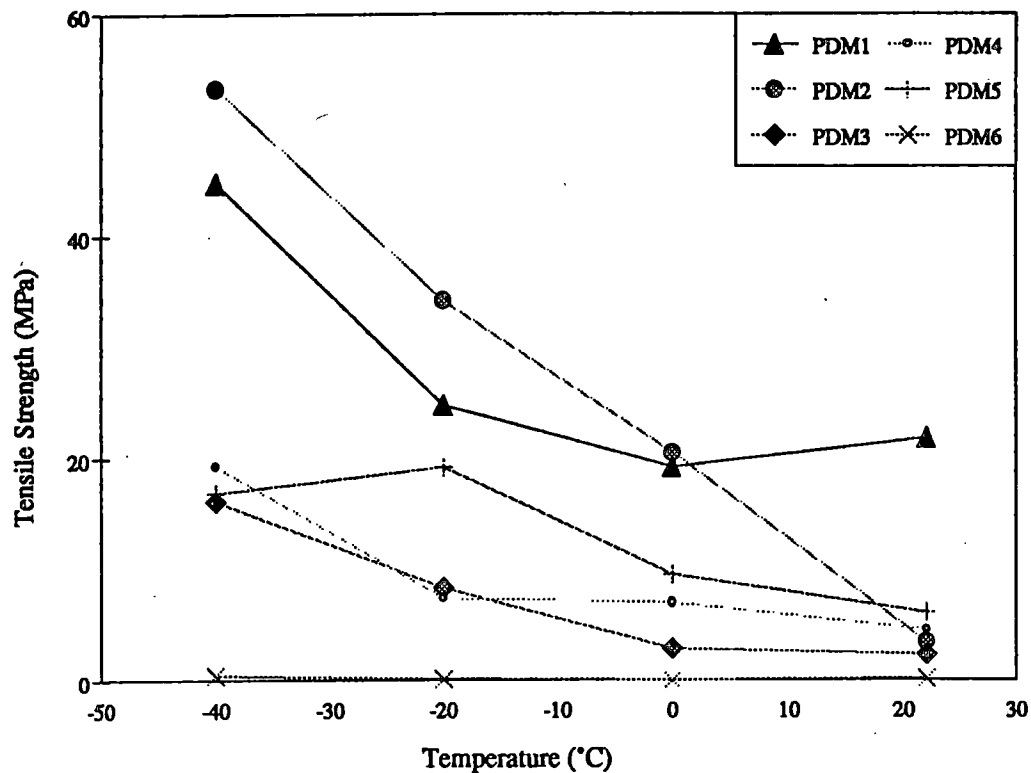


Figure B6

Effect of Cold Temperature on Elongation

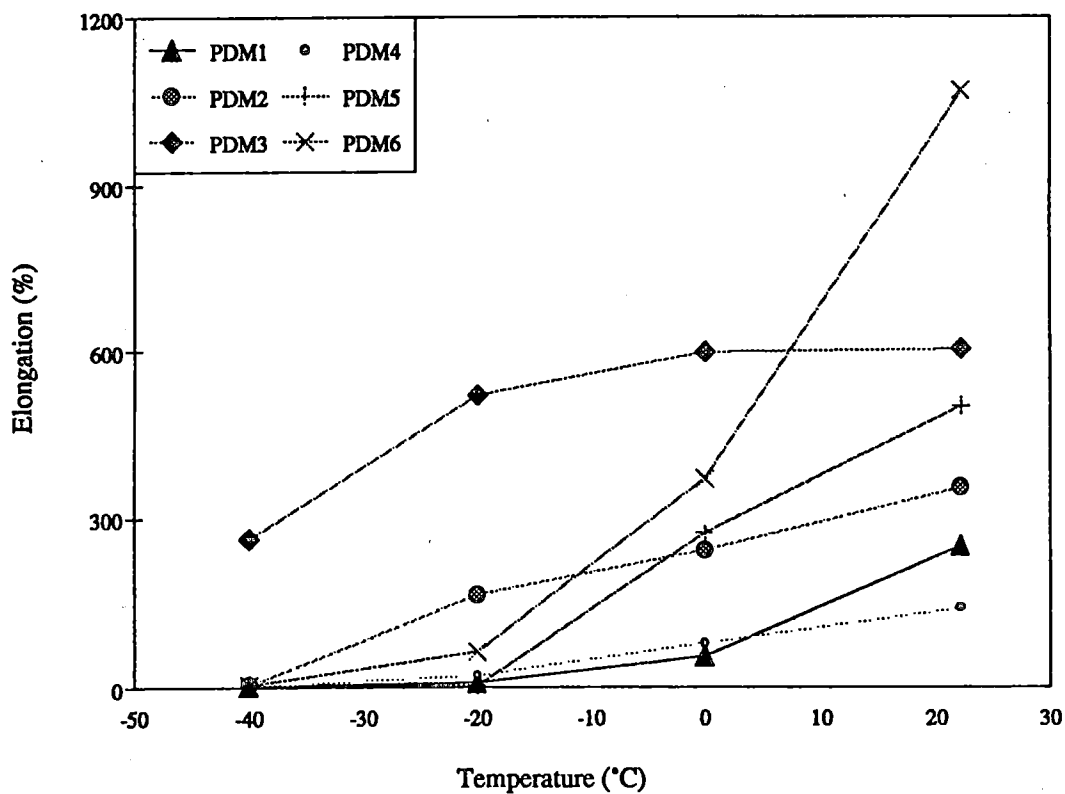


Figure B7
Thickness Changes Upon Exposure to Motor Oil

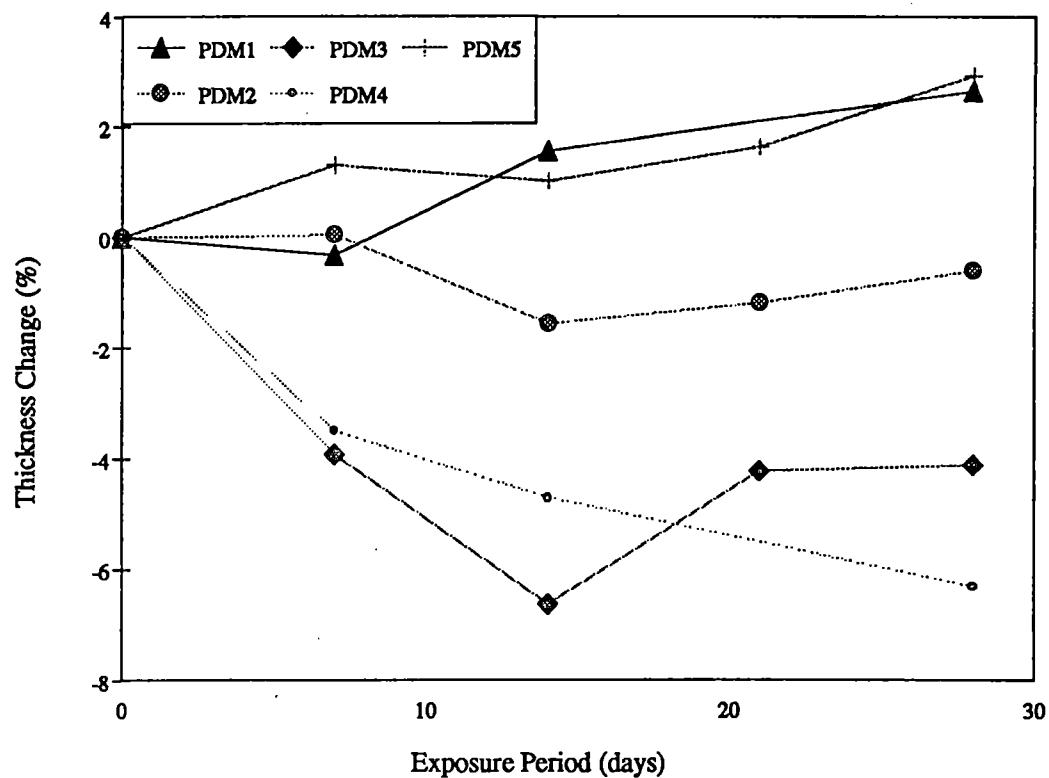


Figure B8
Thickness Changes Upon Exposure to Ethylene Glycol

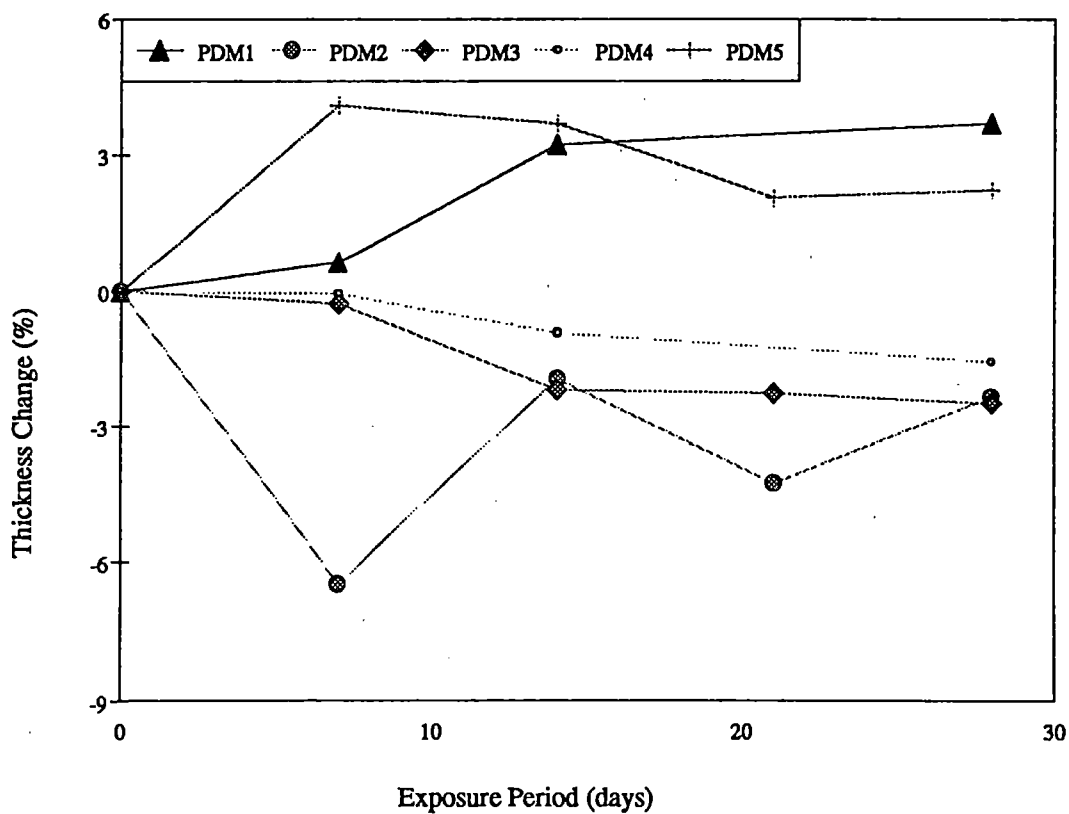
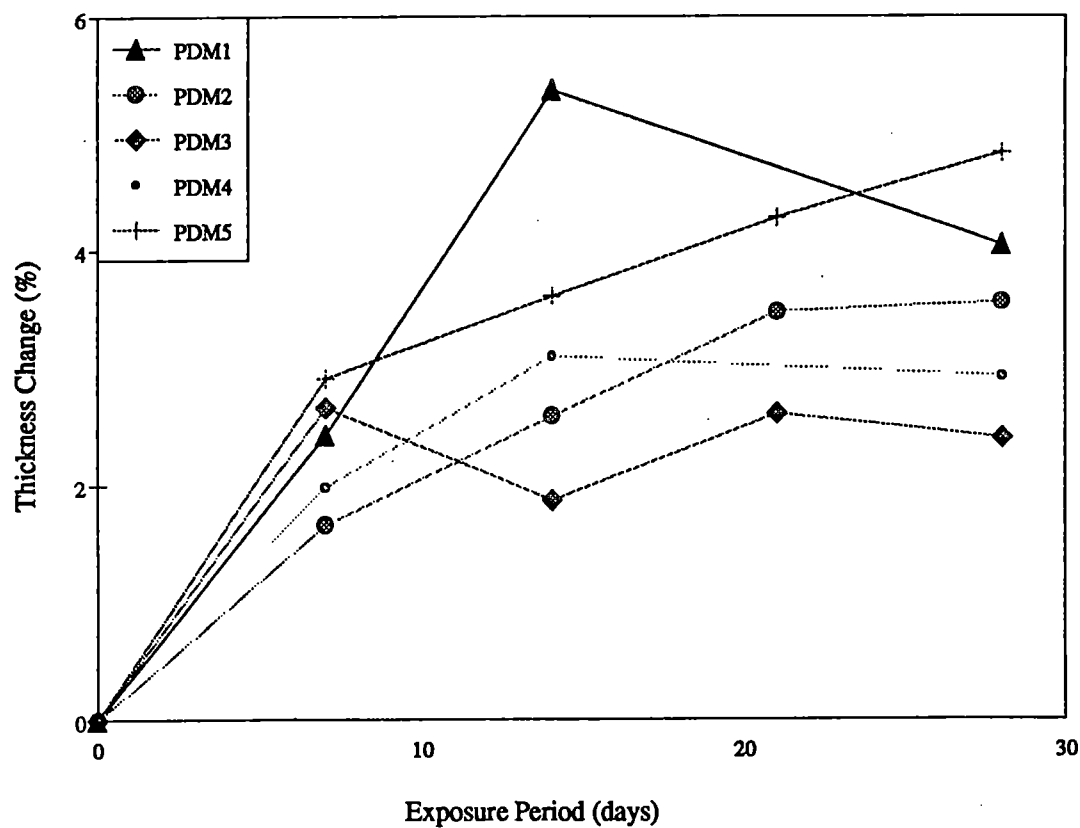


Figure B9
Thickness Changes Upon Exposure to Water



APPENDIX C

Specimen Types and Test Examples

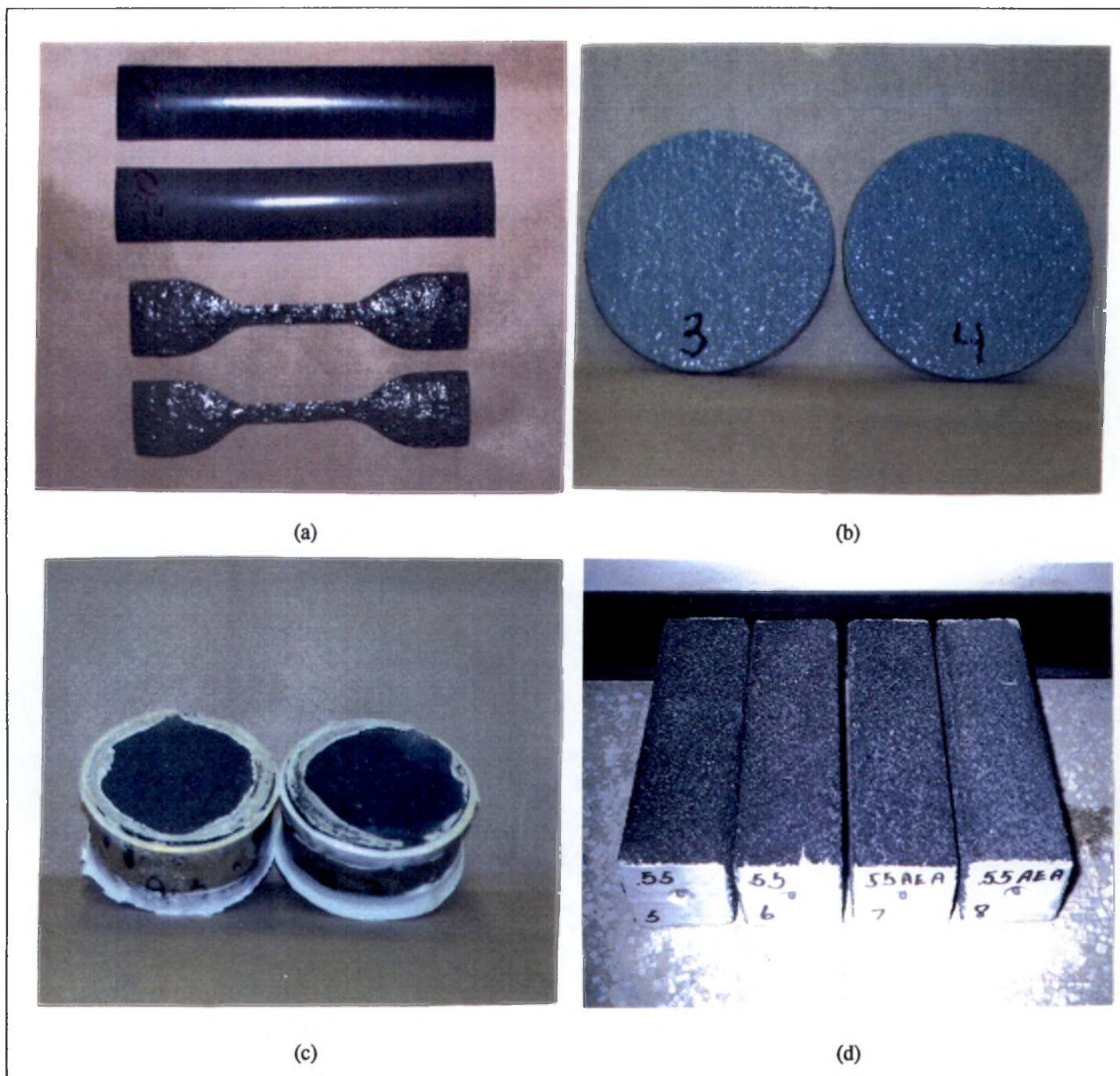


Figure C1. Specimen Types Used : (a) free film coupons and dumbbells, (b) 6" dia. discs for WVT, (c) 4" discs for chloride ion permeability, (d) 12"x3"x3" prisms

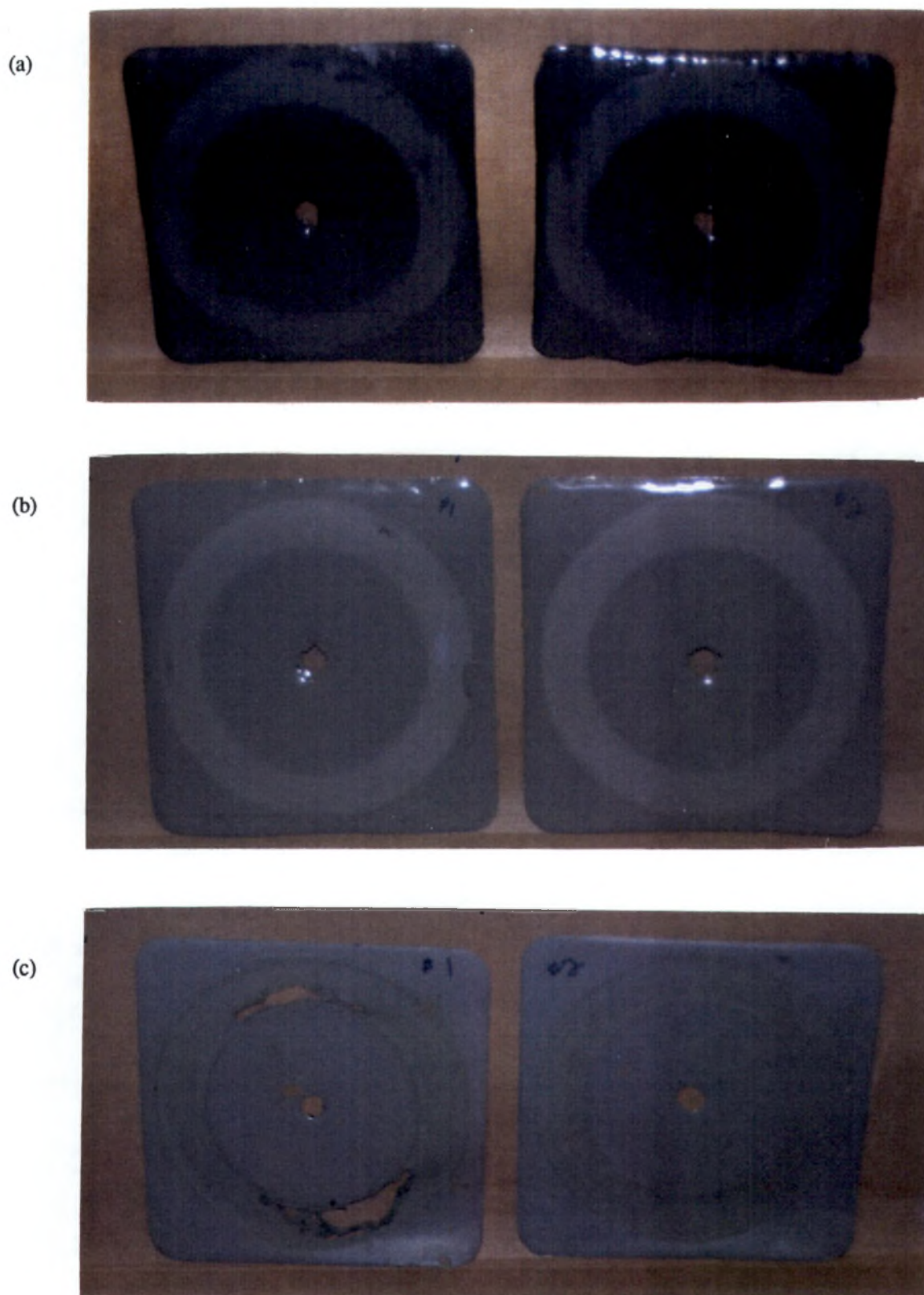


Figure C2. Abrasion Resistance of Free Film Specimens: (a) PDM-1, (b) PDM-2, (c) PDM-3. All samples abraded with CS-17 wheels, 1000g per arm.



Figure C3. Abrasion Resistance of Free Film Specimens: (a) PDM-4, (b) PDM-5. All samples abraded with CS-17 wheels, 1000g per arm.

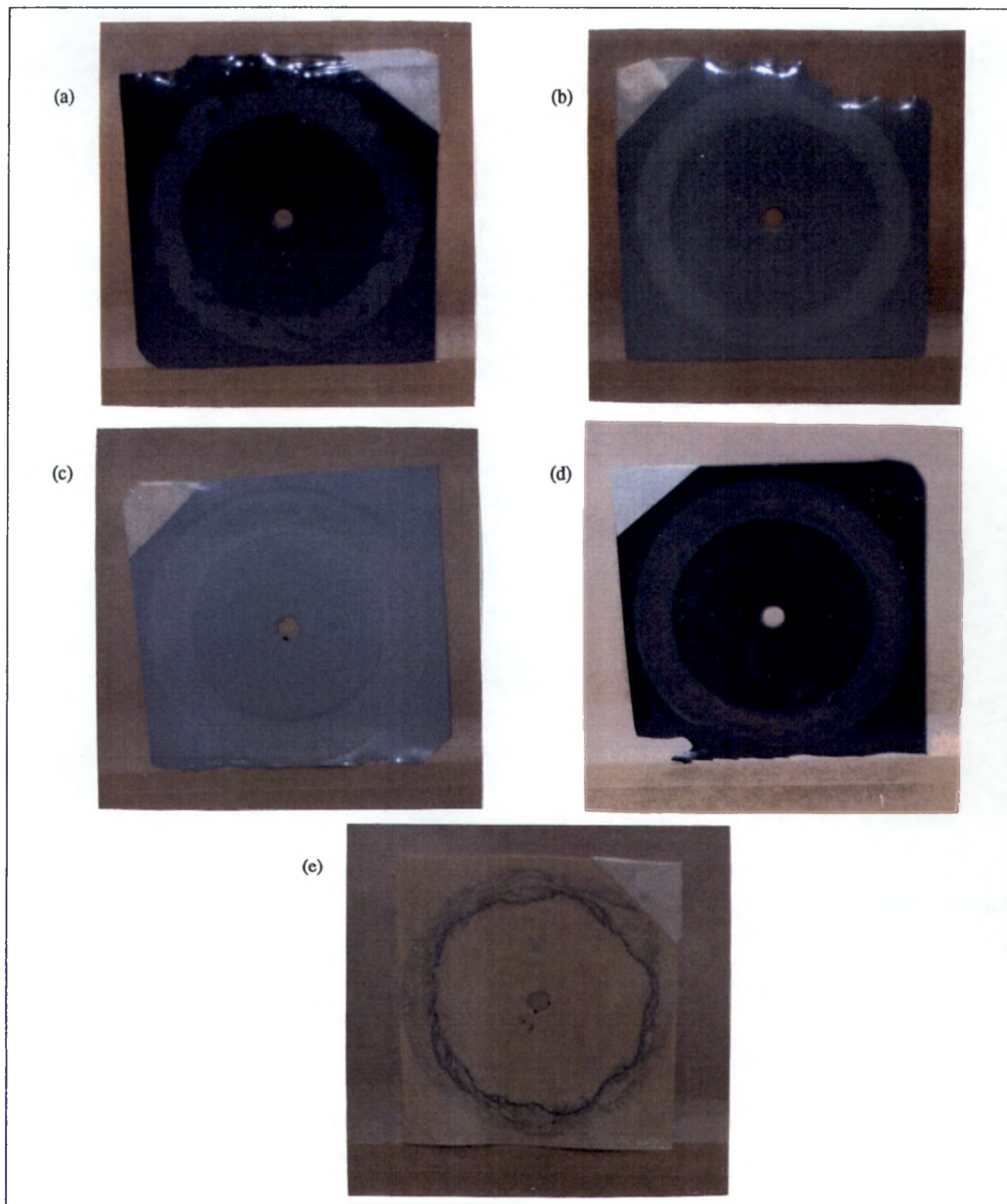


Figure C4. Abrasion Resistance of Free Film Specimens: (a) PDM-1, (b) PDM-2, (c) PDM-3, (d) PDM-4, (e) PDM-5.

All samples abraded with H-10 wheels, 1000g per arm.

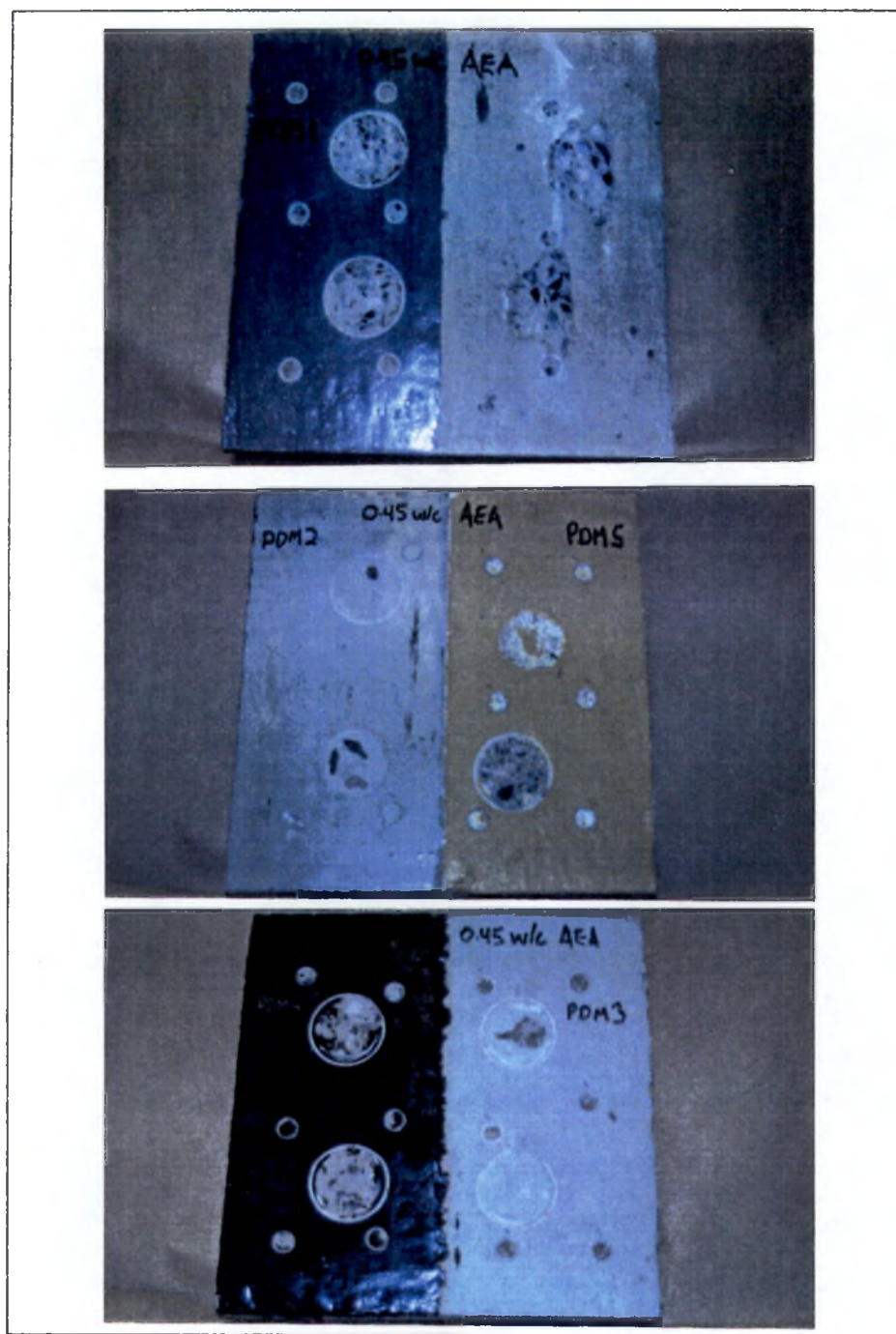
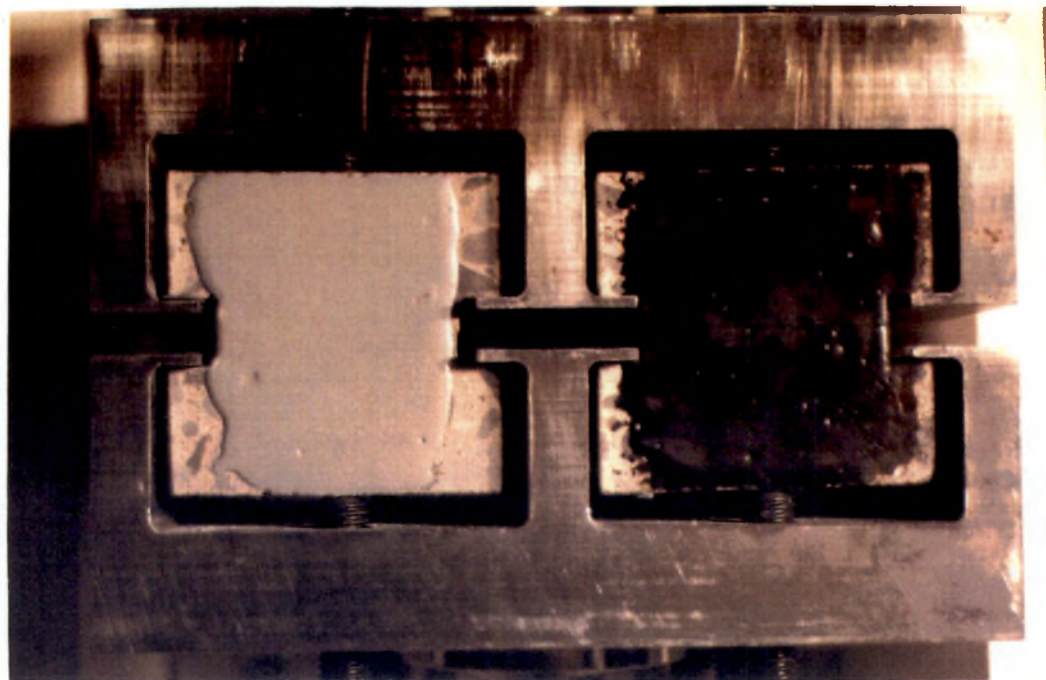
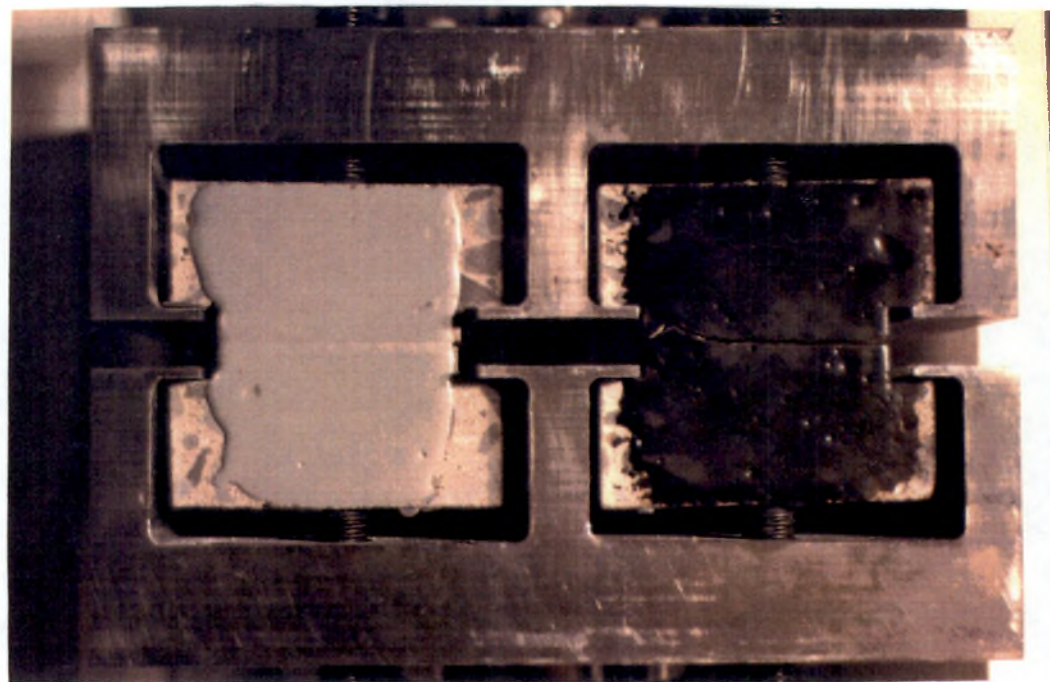


Figure C5. Adhesion of Waterproofing Membrane to Concrete, water/cement 0.45 air entrained



(a)



(b)

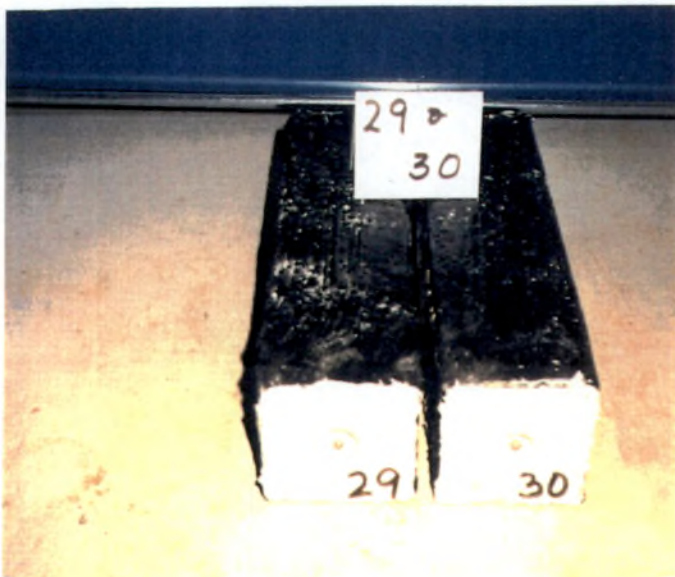
Figure C6. Crack Bridging of Waterproofing Membranes: PDM-3 (left), PDM-4 (right)
(a) prior to testing, (b) at full extension.



(a)



(b)



(c)



(d)

Figure C7. Effect of Freeze/Thaw cycling on PDM-6: (a) water/cement 0.45, (b) water/cement 0.55, (c) water/cement 0.45 air entrained, (d) water/cement 0.55 air entrained

APPENDIX D
Infrared Analysis
of
Elastomeric Membranes

FTIR Analysis Of Parking Garage Membranes

Introduction

It is well known that many polymers undergo degradation upon exposure to UV light.¹⁻⁴ Chemical bonds such as C-C, C-H, O-H, C-Cl, C=O and C=C-C=C absorb radiation below 200nm. Although the polymer itself might not contain these functional groups, most contain additives such as plasticizers, which do contain such groups. The end-result of such degradation can be a combination of (a) chain-scission (breaking of bonds), (b) crosslinking (creating new bonds) or (c) oxidation. This leads to the creation of free-radicals, carbonyl, carboxyl, or hydroxyl groups. These changes, depending on their extent, are often observable by chemical techniques such as Fourier-transform infrared-photoacoustic (FTIR-PAS) spectroscopy and dynamic mechanical analysis (DMA).

The FTIR-PAS spectra of five polymeric (four polyurethane-based and one neoprene-based) waterproofing is described below. The procedure used was relatively simple; the spectrum for the unexposed control sample was obtained and used as a reference. The spectra of the UV exposed samples were then subtracted from the appropriate reference. In order to keep this discussion as simple as possible, only the spectral subtractions, that are provided in the adjoining figures, will be discussed.

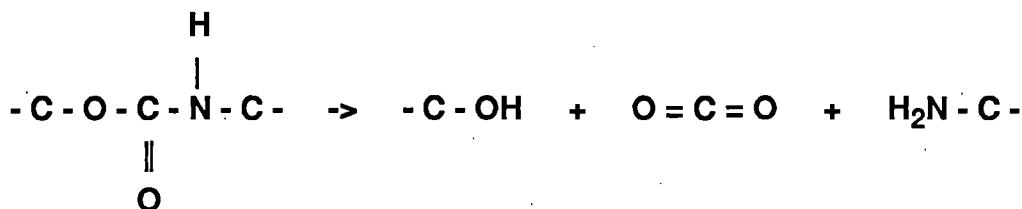
Results of FTIR Analysis

PDM-2

The PDM-2 is a two component polyurethane membrane. The sample had undergone a colour change on exposure UV radiation; originally grey and turning yellow. It is important to note that only the side exposed to UV radiation changed colours. Although photoacoustic spectroscopy is a bulk technique, the depth of penetration does vary. Hence, by analyzing the yellow side of the membrane and the grey side of the membrane, some interesting observations were noted.

The subtraction of the reference from the still grey side of the weathered specimen, revealed that some of the overall composition changed slightly. For example, a slight increase in CH peaks ($2800-3000\text{ cm}^{-1}$) was observed. There were also more intense carbonyl bands ($\sim 1750\text{ cm}^{-1}$) and at the same time a negligible decrease in C=C bands; this usually is indicative of oxidative degradation. The growth of the carbonyl band is usually an indicator of changes in mechanical properties, e.g., loss of ductility.

The yellow side of the membrane has undergone much greater chemical degradation. More C=C (this could explain to a certain degree the yellowing of the membrane) and C=O bands have appeared. These bands could have been produced by a free-radical degradation process which is common with UV radiation. The increase in OH bands is indicative of further decomposition. It is possible that this increase is indicative of polyurethane degradation by a combination of water and UV which is as follows:



The above scheme indicates that upon breakdown of the urethane, additional OH peaks and NH₂ peaks would appear. Unfortunately, the broadness of the OH bands prevents the detection of the NH₂ peaks. However, the region has definitely undergone significant change. Another area where peaks due to NH₂ can be observed is in the 1490 to 1620 cm⁻¹ region. A small peak is observed at ~1580 cm⁻¹ that could be due to NH bending deformation. It is also apparent from the above scheme that a decrease should be observed in C-O-C band intensities. These bands appear between 1050 and 1300 cm⁻¹. The sharp decrease at approximately 1100 cm⁻¹ can be attributed to the cleavage of the C-O-C in the membrane.

PDM-1

This parking garage membrane is also polyurethane-based. The unexposed side contained no granules. A subtraction of this sample from the unexposed control revealed no difference. The side with granules did, however, undergo some minor changes. The chemical changes are similar to the PDM-1 sample but the intensities are much smaller, thereby implying fewer changes. One could speculate that perhaps the granules acted as a protective shield against UV radiation.

PDM-3

PDM-3 is a moisture cured polyurethane that changed from a glossy texture, prior to weathering, to a dull finish after UV radiation. After weathering, both sides were found to have undergone some chemical changes, however, the glossy (non directly exposed) was barely affected. Overall, this membrane underwent a similar degradation mechanism as the previous two samples. There is, however, a peak at ~2500 cm⁻¹ which cannot be readily explained.

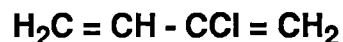
PDM-4

PDM-4 is a coal tar extended epoxy-polyurethane blend. This parking garage membrane underwent very little change in chemical composition after UV weathering. There is a slight increase in OH, C=O and C=C bands. This increase in intensity is comparable to the amount of atmospheric CO₂ detected by FTIR (doublet at ~2400 cm⁻¹). Moreover, a slight loss of CH₂ was detected as evidenced by the negative peak at 1430 cm⁻¹. However, all these changes are negligible and could be attributed to inhomogeneity of the material.

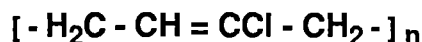
PDM-5

PDM-5 is the only membrane in this series that is neoprene based. Neoprene is the name given to polymers of chloroprene.⁵ The presence of the electronegative chlorine enables the polychloroprene rubber to be more resistant to general weathering (e.g., air oxidation and ozone) than natural rubber. Unlike natural rubber, polychloroprene turns brittle on weathering. The

most important factor affecting the degradation of this unsaturated rubber is ozonolysis. The ozonolysis can lead to the formation of C=O bonds. Moreover, some dehydrochlorination can occur which leads to the formation of C=C linkages (chain-scission). Part of the degradation process involves crosslinking and therefore it is difficult to obtain a complete understanding of this process.



chloroprene



Polychloroprene (neoprene)

The PDM-5 sample, upon weathering, turned yellow-brown. This is consistent with the formation of conjugated double bonds (e.g., C=C-C=C). The side that did not change colour showed minimal change in composition. The brown side did, however, show a decrease in CH band intensity which was accompanied by increases in OH, C=O and C=C peaks. All of this is compatible with the above mentioned degradation process.

References

1. Schnabel, W., Polymer Degradation: Principles and Practical Applications, MacMillan Publishing Co., Inc., New York, 1981.
2. Wypych, J., Weathering Handbook, Chemtec Publishing, Toronto, 1990.
3. Davis, A., Sims, D., Weathering of Polymers, Applied Science Publishers Ltd., England, 1983.
4. Feldman, D., Polymeric Building Materials, Elsevier Applied Science, New York, 1989.
5. Mark, H. F., Bikales, N. M., Overberger, C. G., Menges, G., Kroschwitz, J. I., Encyclopedia of Polymer Science and Engineering, Volume 3, John Wiley and Sons, USA, 1985, pp.441-462.

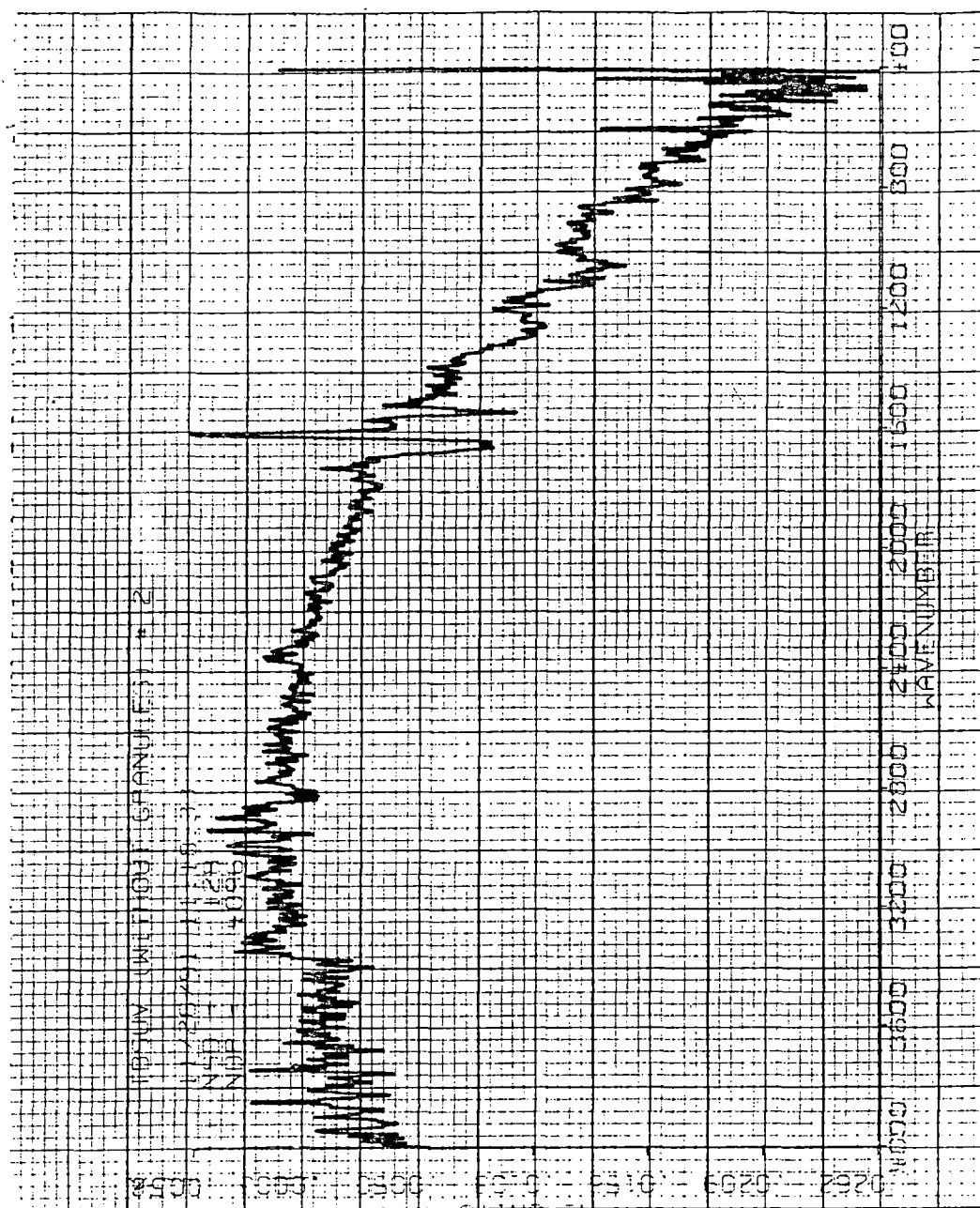


Figure D1 FTIR Spectra of PDM-1 Membranes Exposed to UV Radiation

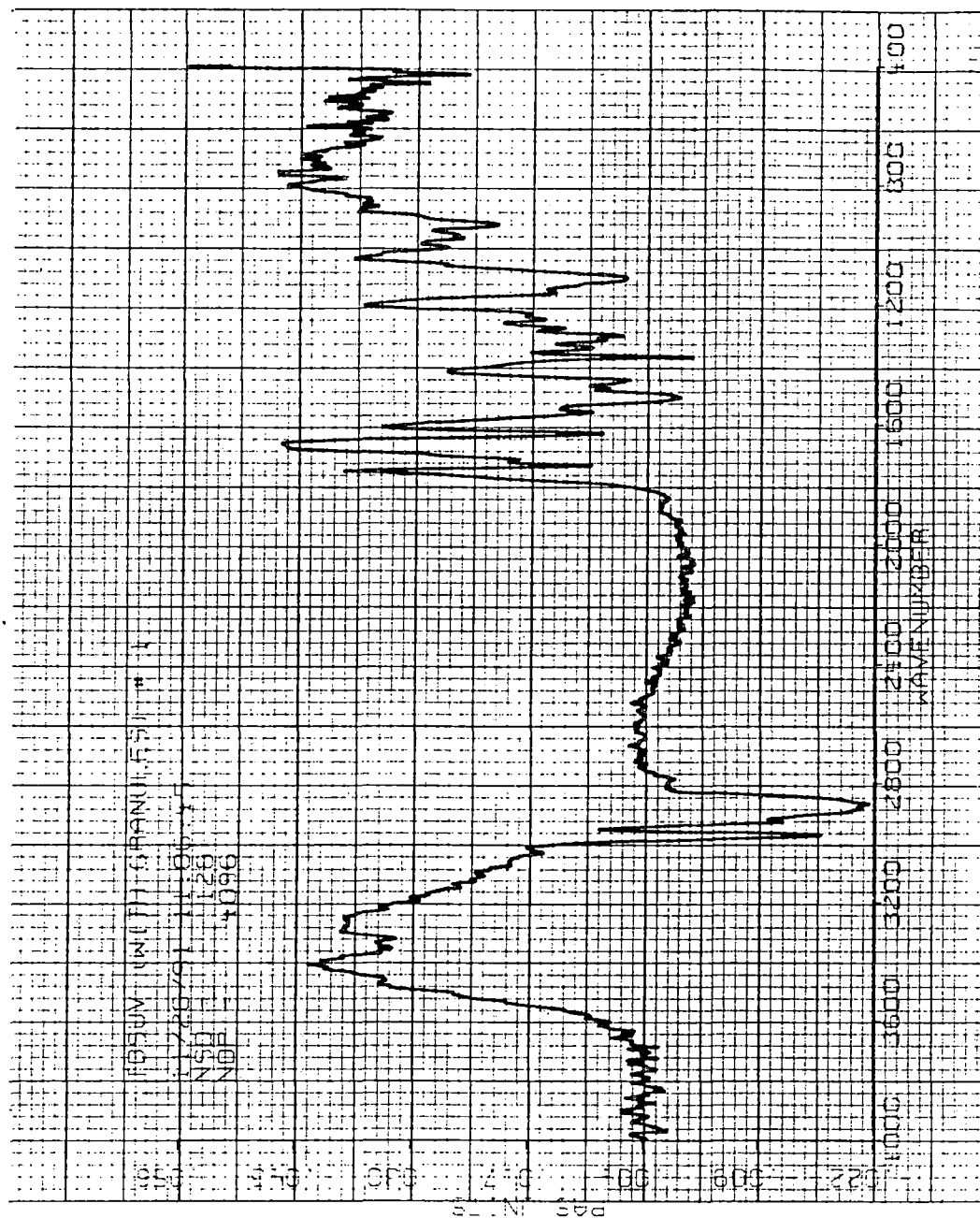


Figure D2 FTIR Spectra of PDM-1 Membranes not Exposed to UV Radiation

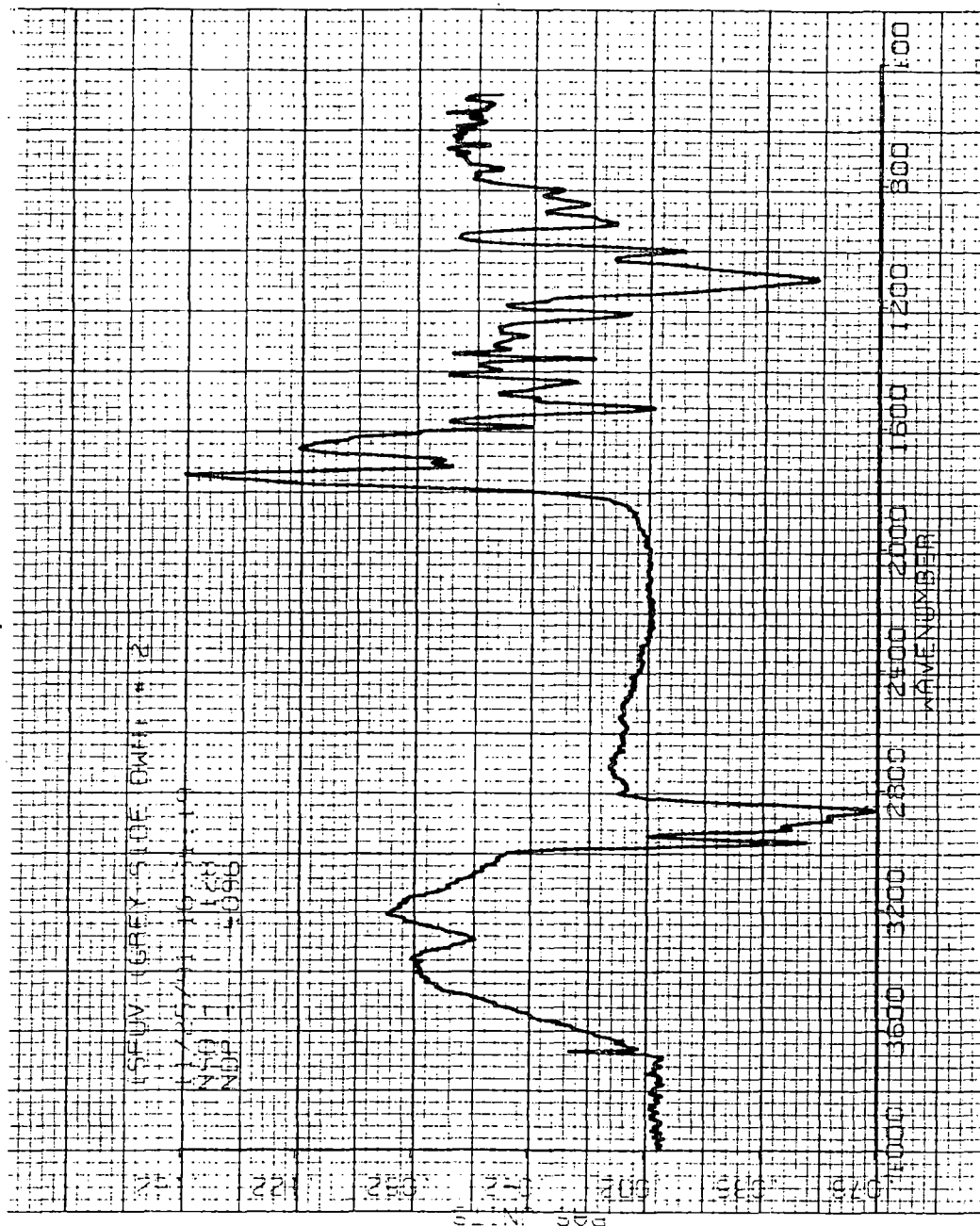


Figure D3 FTIR Spectra of PDM-2 Membranes Exposed to UV Radiation

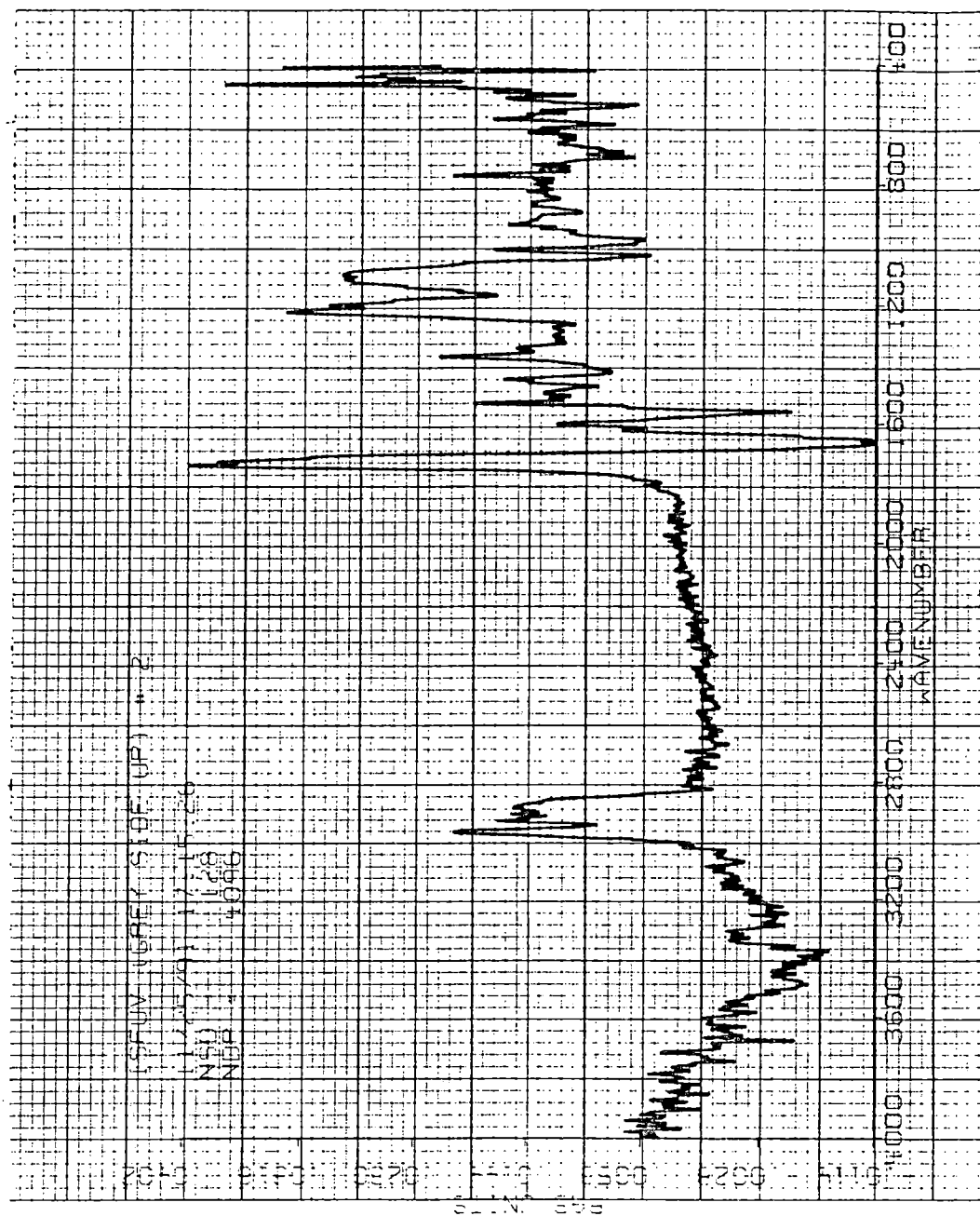


Figure D4 FTIR Spectra of PDM-2 Membranes not Exposed to UV Radiation

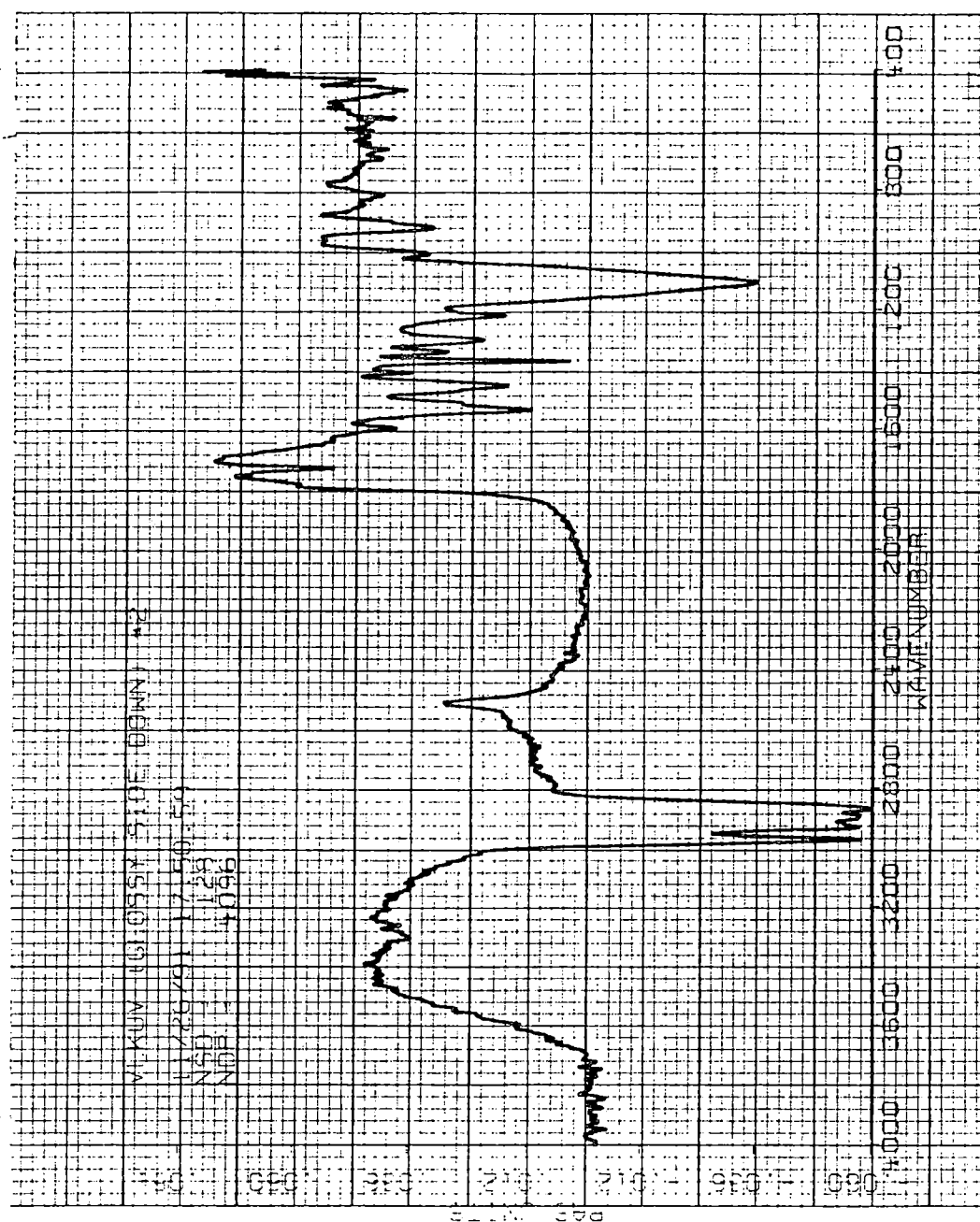


Figure D5 FTIR Spectra of PDM-3 Membranes Exposed to UV Radiation

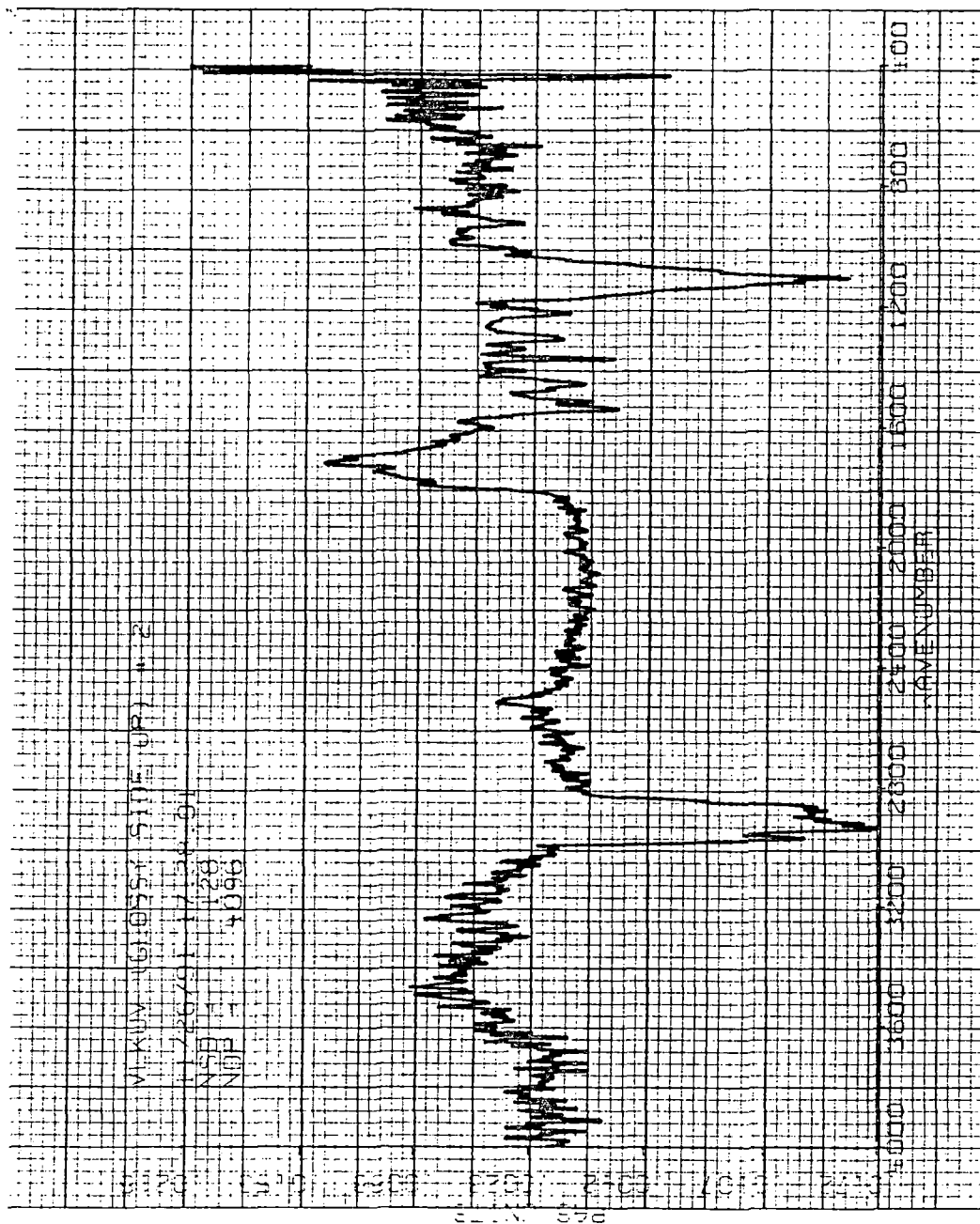


Figure D6 FTIR Spectra of PDM-3 Membranes not Exposed to UV Radiation

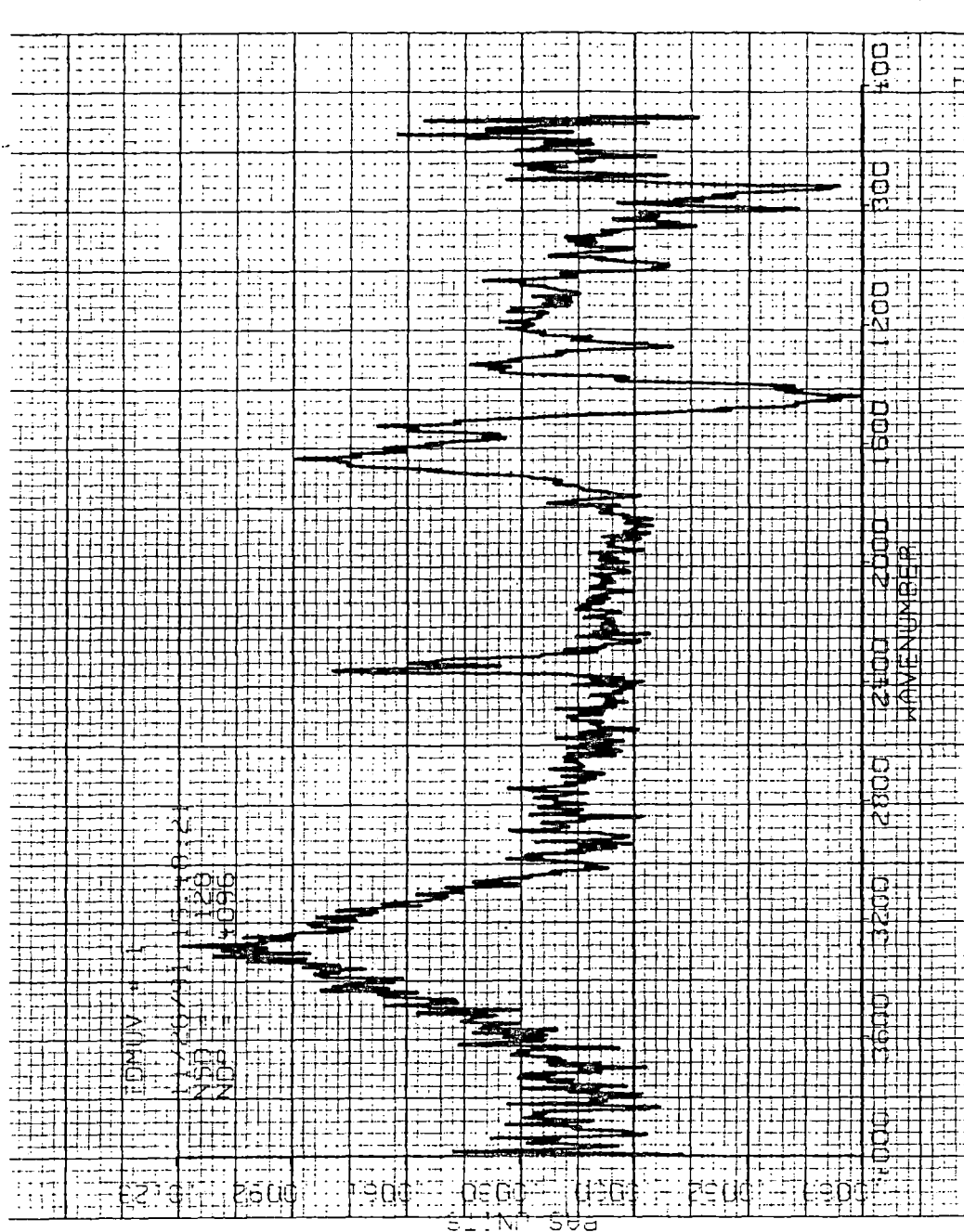


Figure D7 FTIR Spectra of PDM-4 Membranes Exposed to UV Radiation

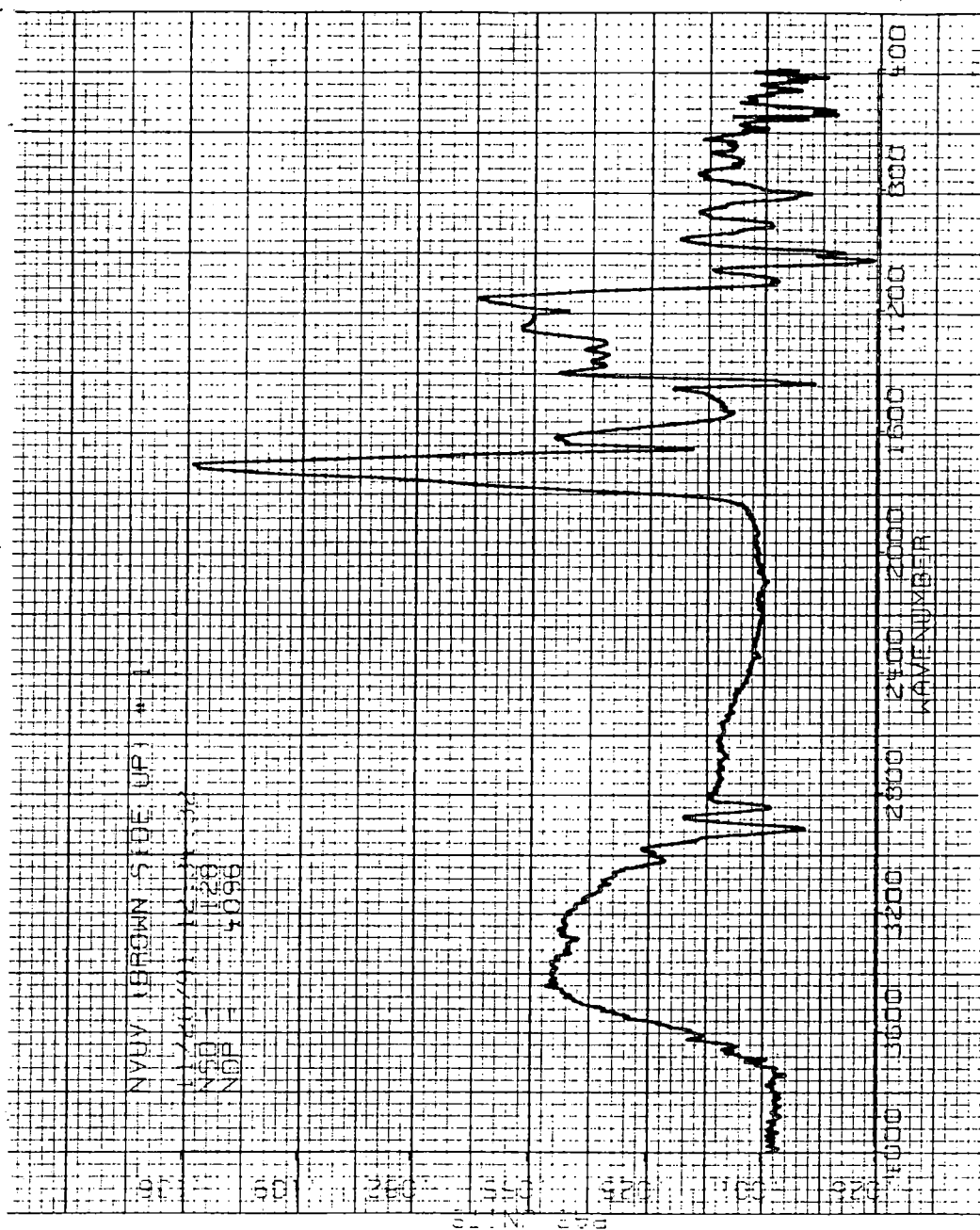


Figure D8 FTIR Spectra of PDM-5 Membranes Exposed to UV Radiation

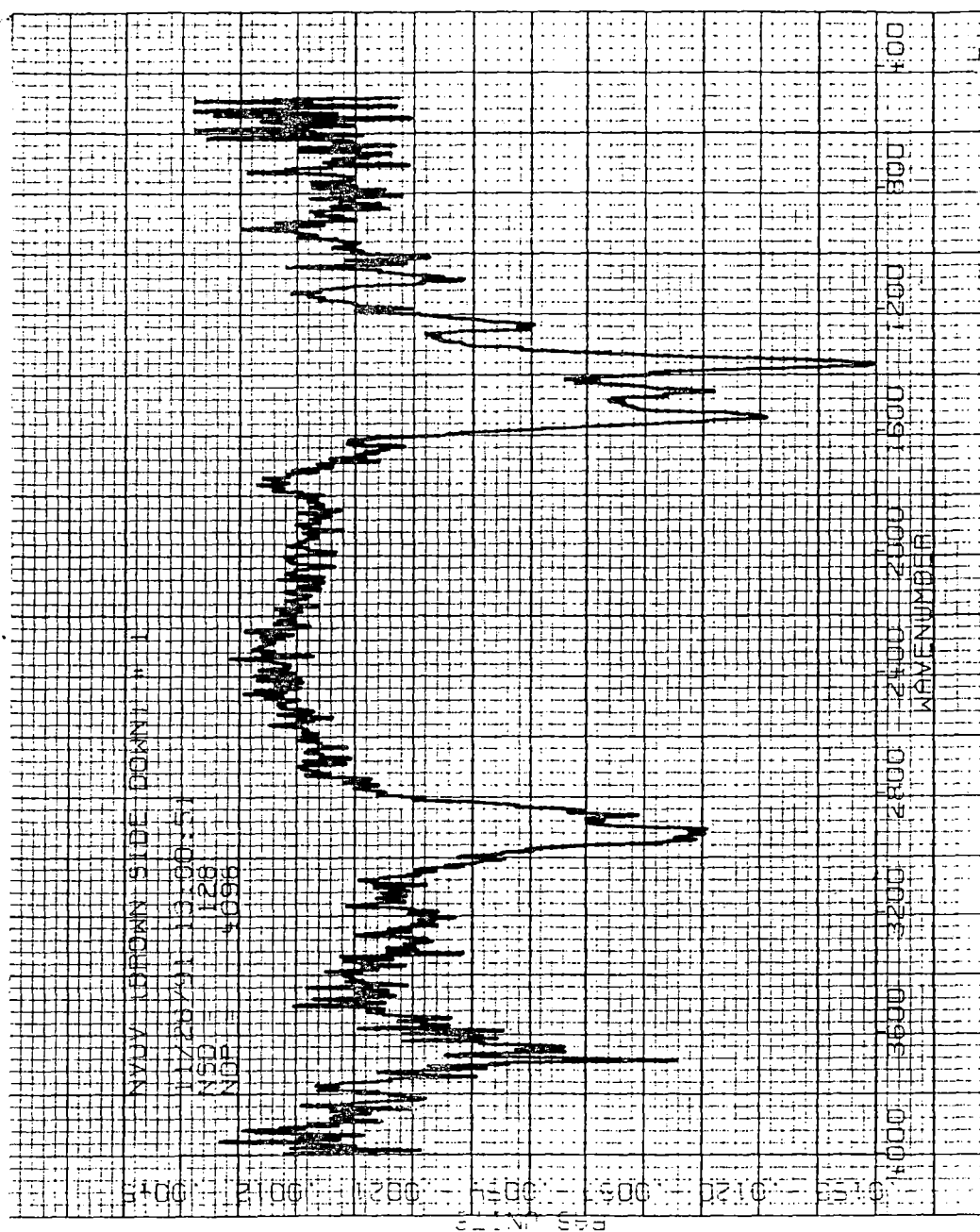


Figure D9 FTIR Spectra of PDM-5 Membranes not Exposed to UV Radiation

APPENDIX E
Summary of Results
and
Selected Thermographs
of
Dynamic Mechanical Analysis
on Elastomeric Membranes

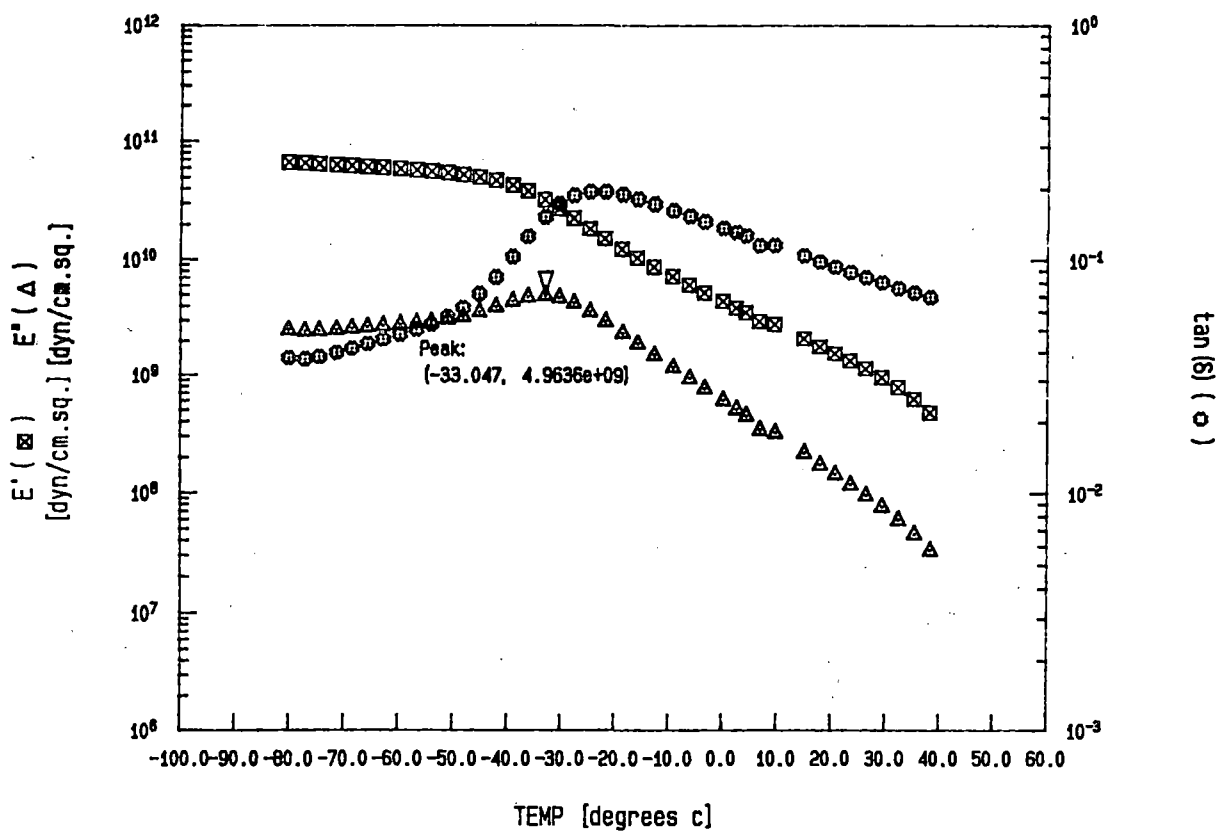
Table D1

Glass Transition Temperatures (°C) of Elastomeric Membranes based on
Dynamic Mechanical Analysis

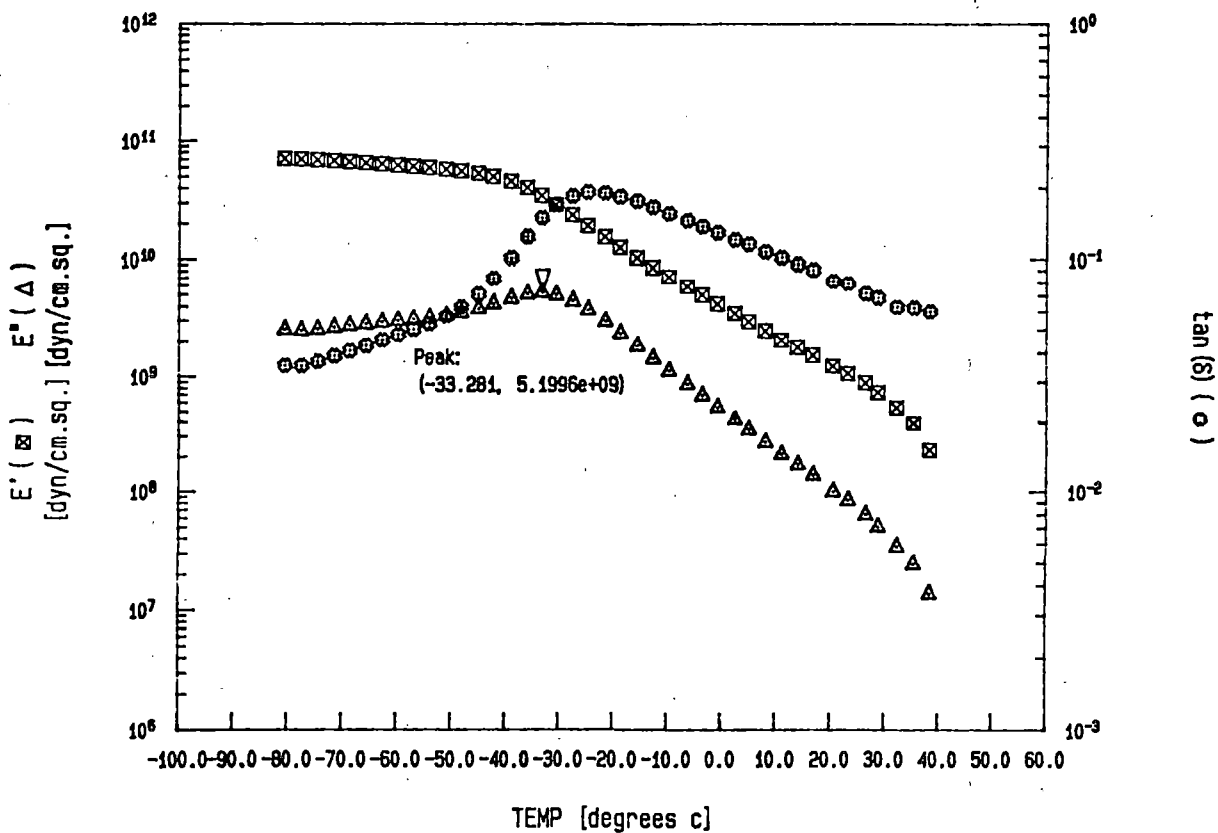
Exposure Condition	Specimen Identification				
	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5
Reference	-32	-36	-49	-35	-17
UV Exposure	-33	-39	-49	-33	-17

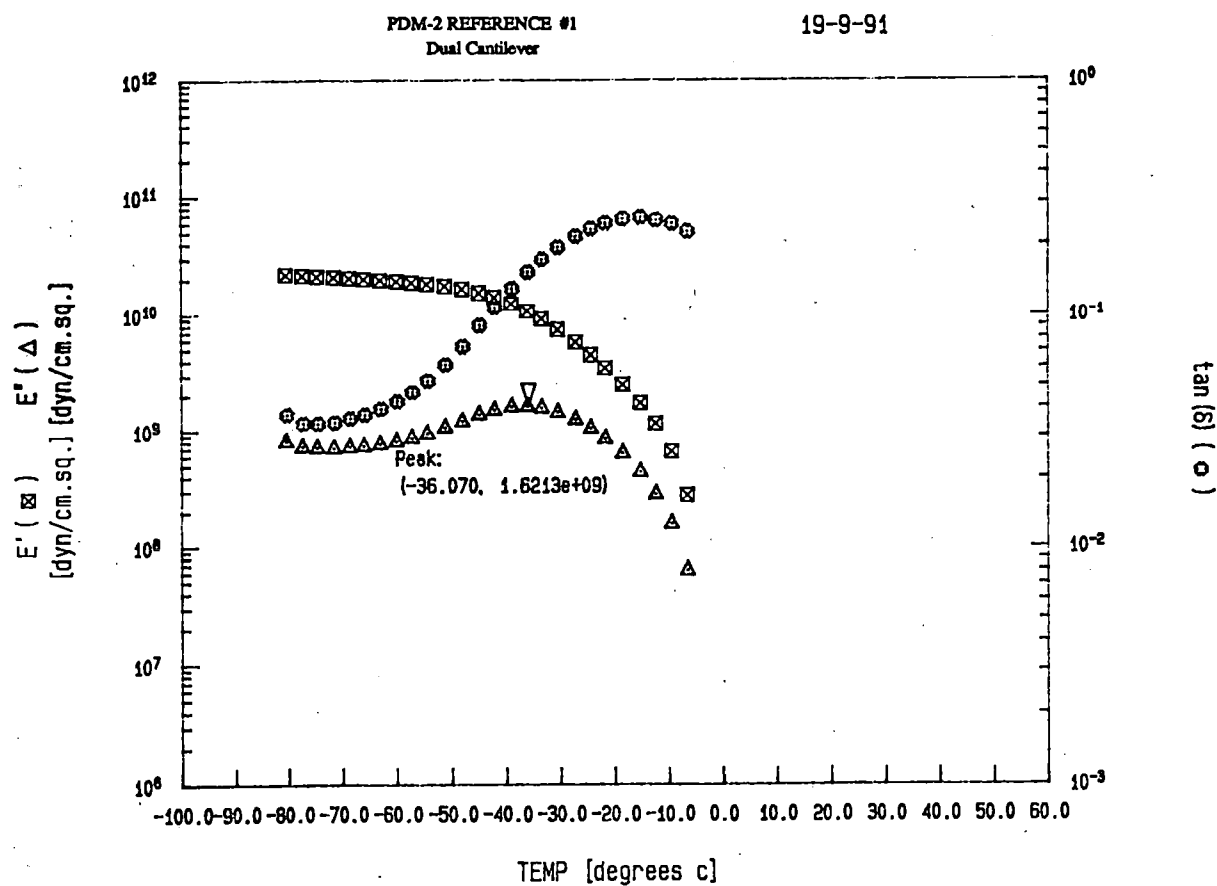
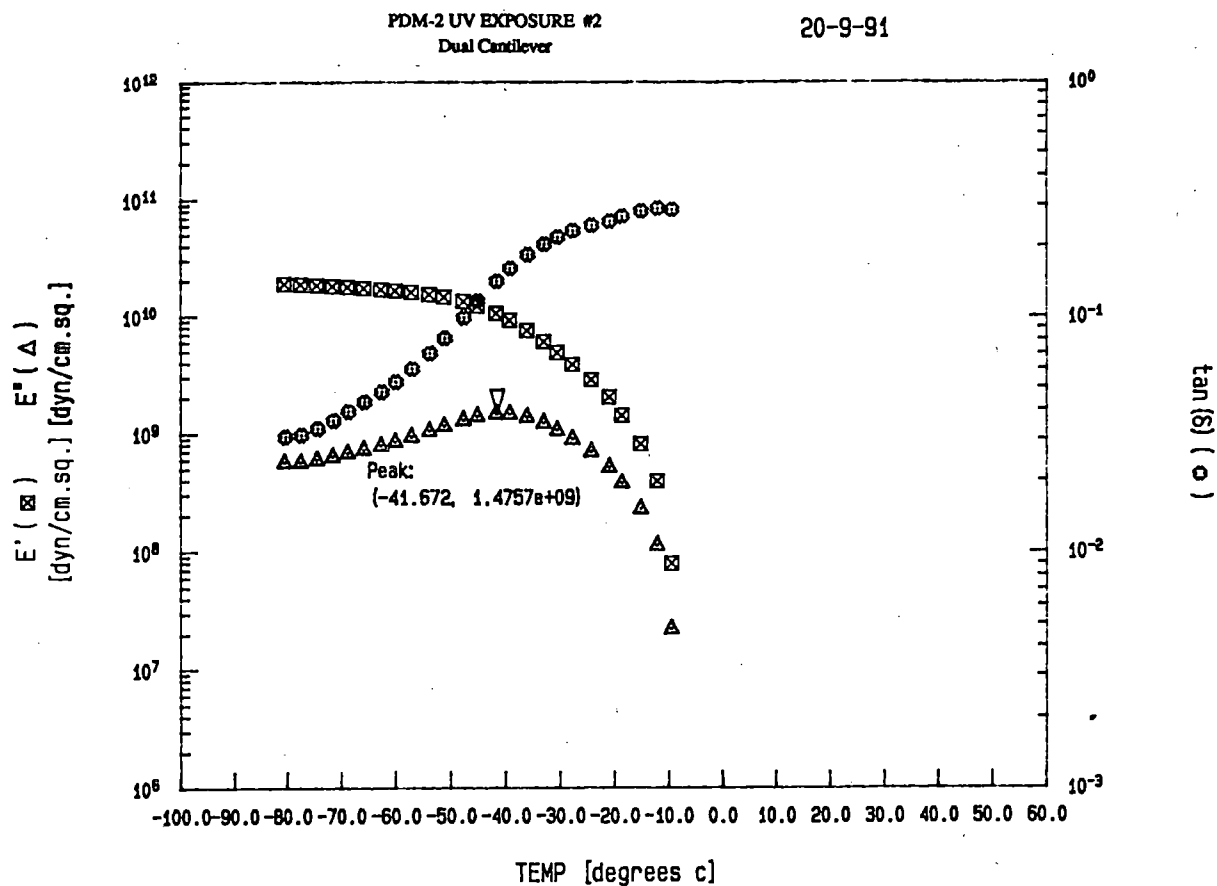
PDM-1 UV EXPOSURE #1
Dual Cantilever

6-09-91

PDM-1 REFERENCE #1
Dual Cantilever

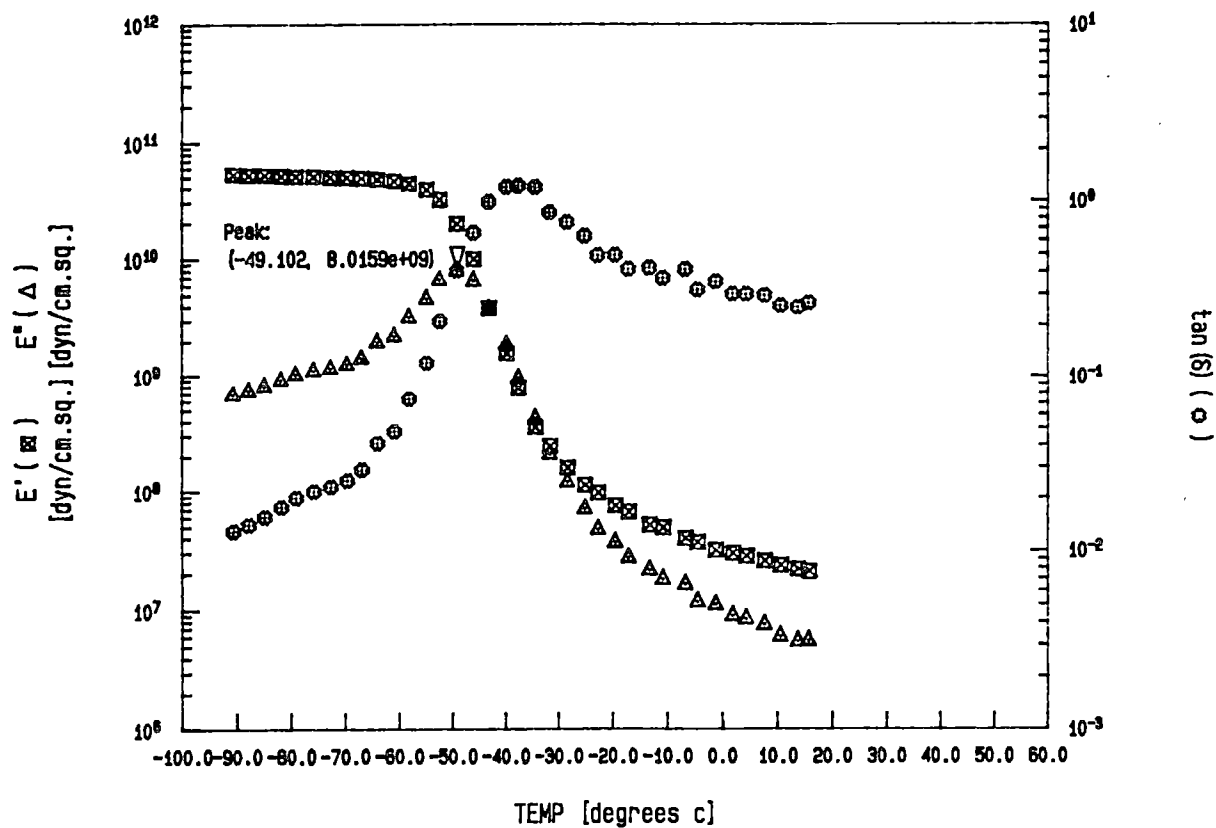
6-9-91



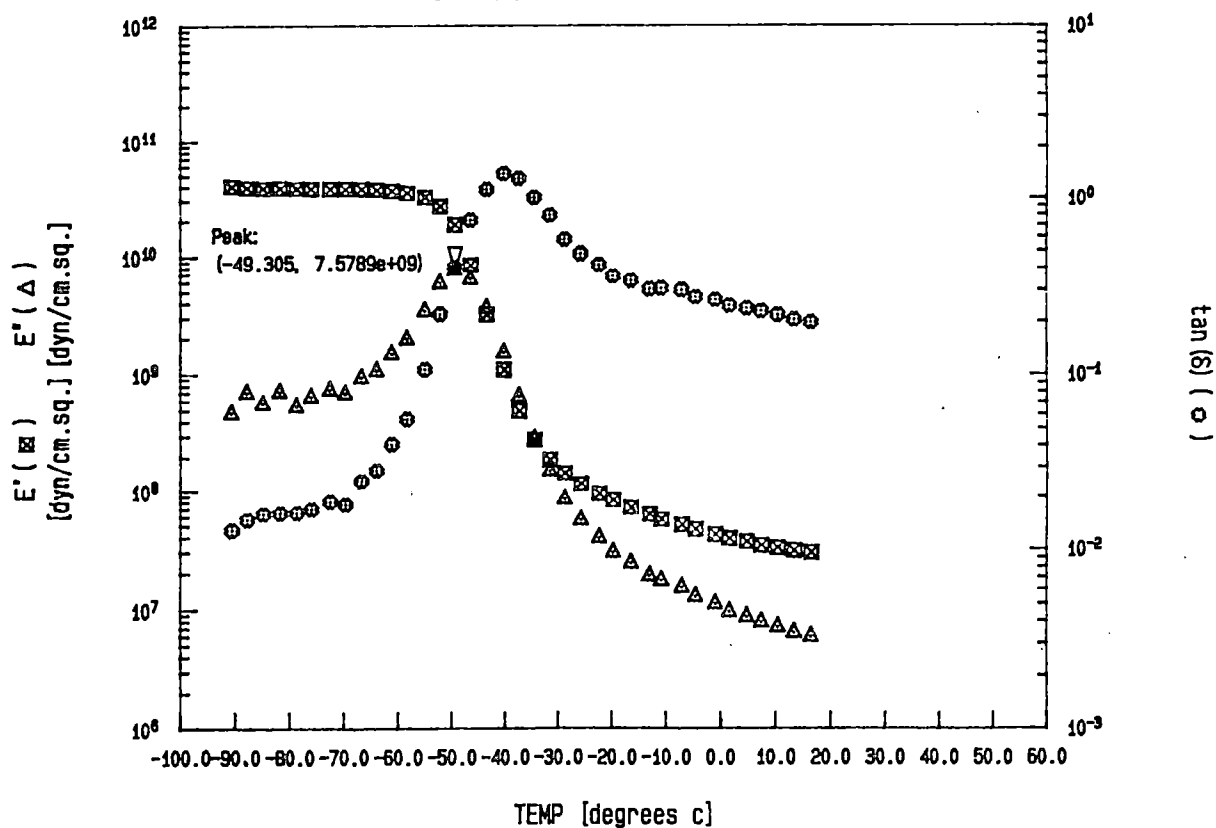


PDM-3 UV EXPOSURE #2
Film Fixture

27-9-91

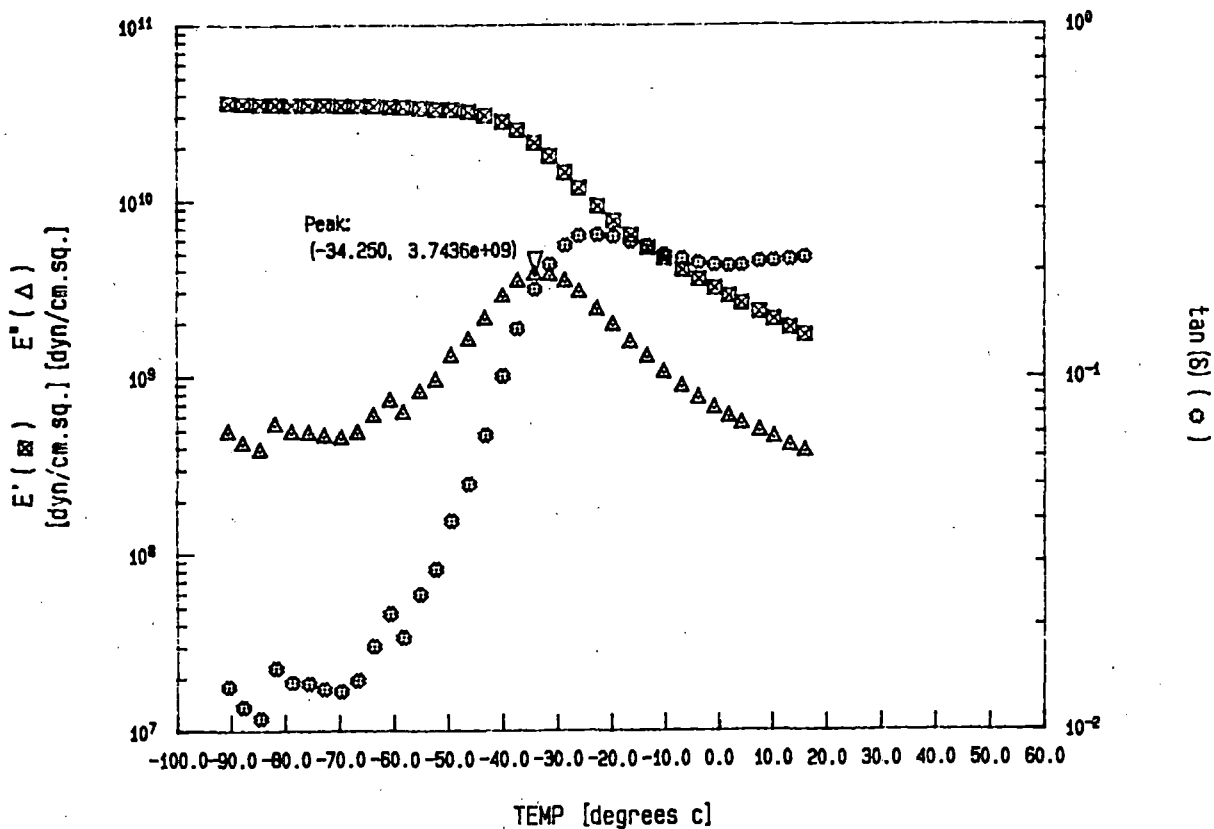
PDM-3 REFERENCE #1
Film Fixture

25-9-91

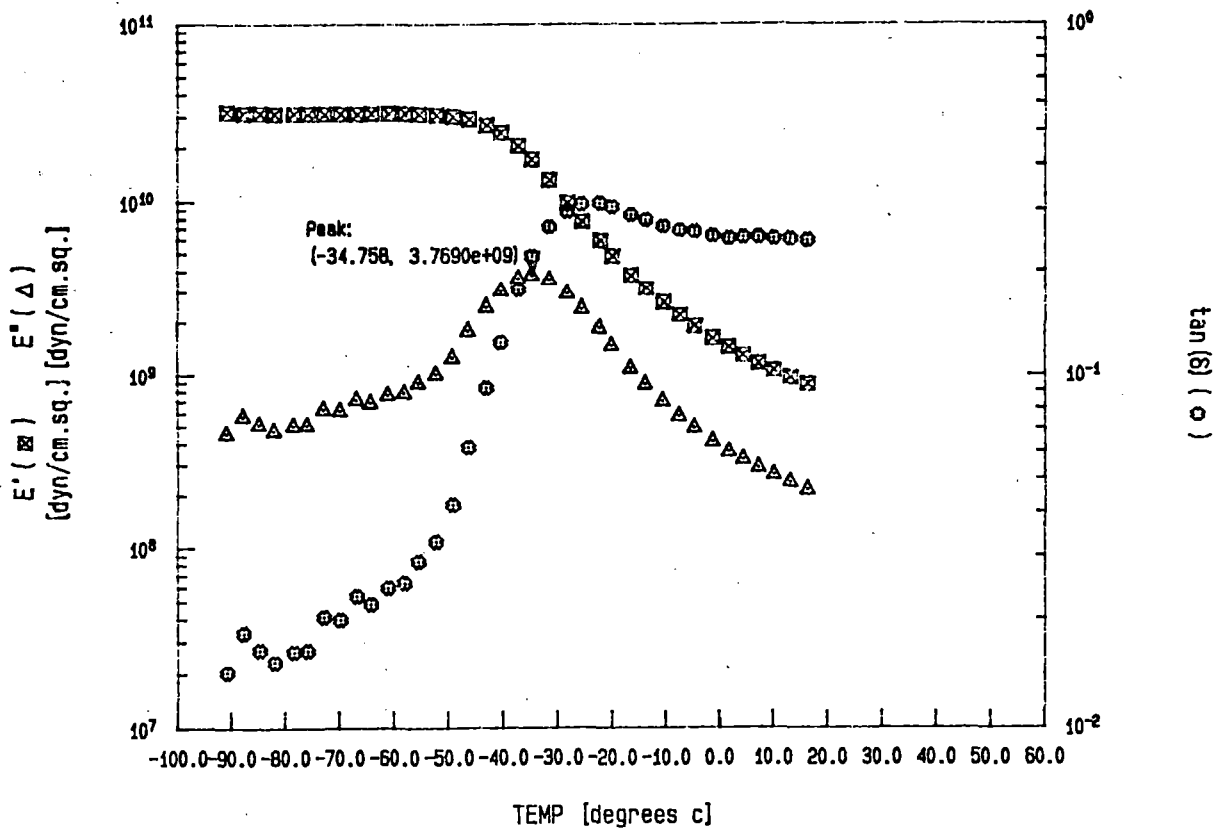


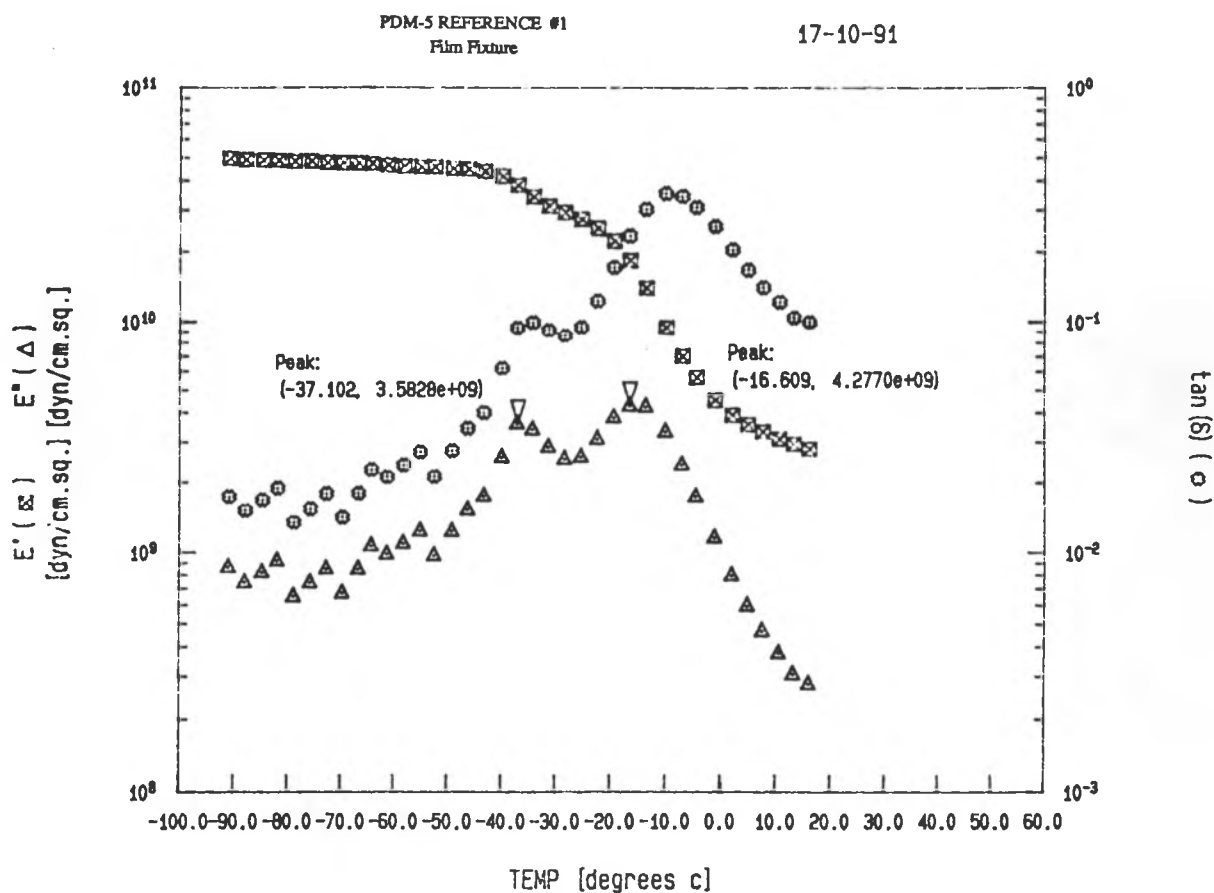
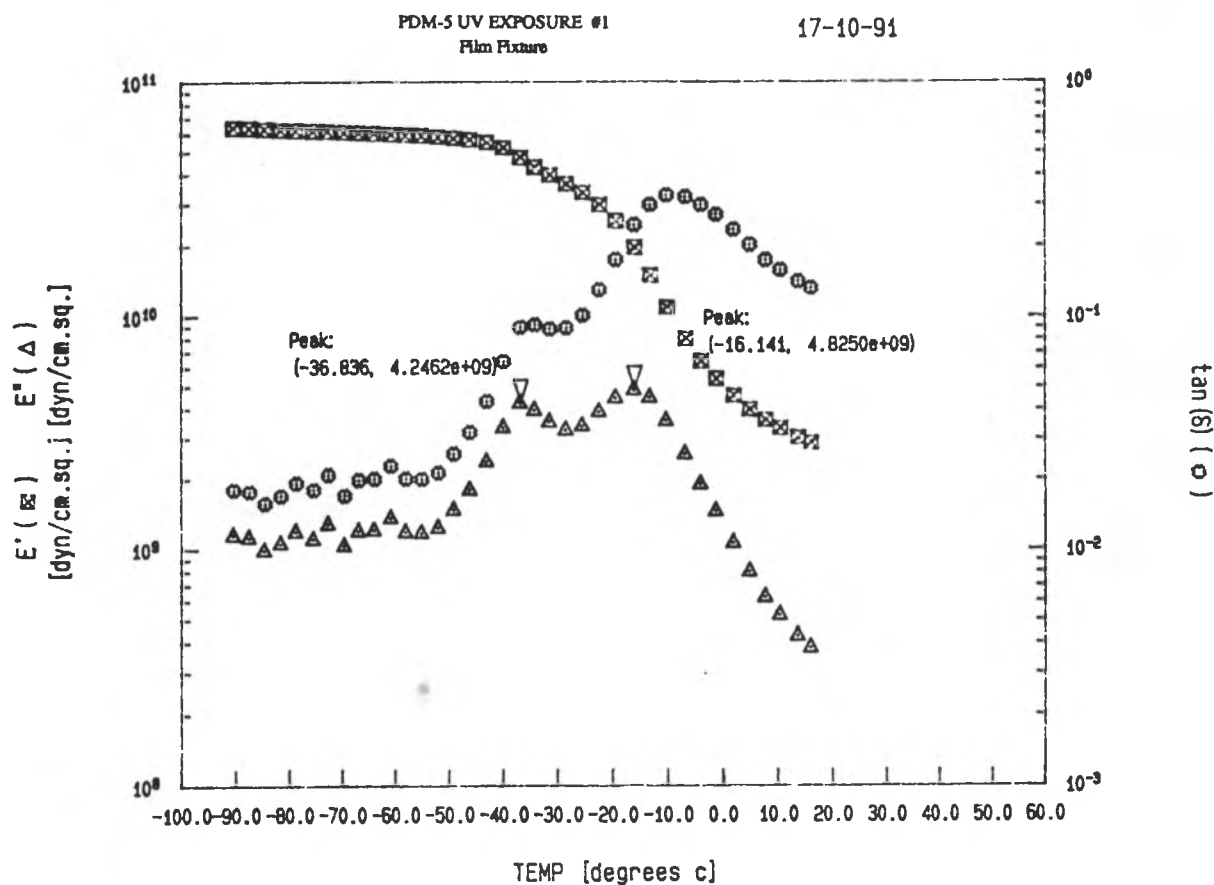
PDM-4 UV EXPOSURE #1
Film Fixture

04-10-91

PDM-4 REFERENCE #1
Film Fixture

04-10-91





APPENDIX F

Table F1
Tensile Strength of Free Film References (MPa)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5	PDM-6
1	23.09	3.006	3.353	4.209	9.166	0.1811
2	22.69	3.183	3.077	4.659	7.785	0.1856
3	24.53	3.334	2.730	4.709	8.887	0.1859
4	20.46	2.703		4.848		0.1832
5				5.359		0.1786
6				5.166		0.1603
7				4.822		
Std. dev.	1.7	0.3	0.5	0.3	0.7	0.01

Table F3
Tensile Strength after Heat Aging (MPa)

Sample	Exposure Period			
	7 days at 40°C	7 days at 100°C	28 days at 40°C	28 days at 100°C
PDM-1 1	20.42	21.02	22.24	17.32
2	excluded	21.20	excluded	17.65
3	25.47	excluded	23.85	14.51
4	25.67	20.34	25.33	14.12
Std. dev.	3.0	0.6	1.5	1.8
PDM-2 1	3.427	3.246	4.239	5.372
2	3.918	3.889	4.226	5.266
3	4.418	3.264	4.096	5.727
4	4.063	3.121	4.415	5.014
Std. dev.	0.4	0.1	0.1	0.3
PDM-3 1	3.726	4.434	3.275	4.513
2	3.447	4.848	3.816	4.168
3	3.456	4.792	3.684	3.777
4	3.639	4.802	2.837	3.387
Std. dev.	0.14	0.2	0.4	0.4
PDM-4 1	6.664	5.199	6.775	2.073
2	6.683	5.263	6.571	1.611
3	6.526	broke	6.239	broke
4	6.418	broke	6.462	broke
Std. dev.	0.12	0.04	0.2	0.6
PDM-5 1	10.410	16.46	11.65	9.715
2	9.247	12.78	9.472	10.350
3	9.479	15.18	8.795	9.167
4	9.769	13.23	6.999	excluded
Std. dev.	0.5	1.7	2.0	0.6
PDM-6 1	0.1433	melted	0.1646	melted
2	excluded	melted	0.1598	melted
3	0.212	melted	0.1489	melted
4	0.1801	melted	0.1526	melted
5	0.1947	melted	0.1759	melted
Std. dev.	0.03		0.01	

Table F2
Elongation of Free Film References (%)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5	PDM-6
1	298.5	366.6	786.6	124.7	785.2	1101
2	295.5	394.3	727.0	140.2	687.2	1119
3	310.9	398.3	584.6	145.9	811.5	1110
4	307.4	323.9		153.9		1072
5				156.0		980
6				142.6		1032
7				135.7		
Std. dev.	7.3	39	88	12	65	54

Table F4
Elongation after Heat Aging (%)

Sample	Exposure Period			
	7 days at 40°C	7 days at 100°C	28 days at 40°C	28 days at 100°C
PDM-1 1	226.2	246.9	223.6	229.5
2	excluded	242.1	excluded	216.7
3	286.6	excluded	230.0	140.8
4	297.5	250.5	256.8	154.7
Std. dev.	38	6	18	44
PDM-2 1	343.3	337.3	314.8	359.4
2	388.9	400.3	373.3	348.5
3	346.7	433.5	341.6	338.6
4	409.7	386.9	465.0	307.4
Std. dev.	32	24	65	22
PDM-3 1	764.4	360.6	490.1	318.9
2	713.3	446.9	375.1	373.0
3	682.5	437.5	737.1	275.8
4	732.6	434.0	453.4	292.7
Std. dev.	34	40	138	42
PDM-4 1	113.9	5.28	88.70	0.516
2	97.1	4.41	87.71	2.351
3	104.5	broke	75.32	broke
4	101.0	broke	83.75	broke
Std. dev.	7	0.6	6	1.3
PDM-5 1	695.5	633.0	737.1	173.3
2	620.6	465.0	611.9	207.4
3	661.8	617.2	586.6	146
4	639.0	485.3	480.2	excluded
Std. dev.	32	87	106	31
PDM-6 1	650.3	melted	640.8	melted
2	excluded	melted	707.3	melted
3	685.6	melted	685.6	melted
4	722.9	melted	722.9	melted
5	754.7	melted	754.7	melted
Std. dev.	80		43	

Table F5
Weight Changes after Heat Aging (%)

Sample		Exposure Period			
		7 days at 40°C	7 days at 100°C	28 days at 40°C	28 days at 100°C
PDM-1	1	-2.23	-3.65	-1.32	-3.02
	2	-2.45	-3.23	-2.02	-2.48
	3	-2.40	-2.67	-1.91	-2.67
	4	-1.68	-2.64	-2.26	-2.19
	Std. dev.	0.3	0.4	0.5	0.35
PDM-2	1	-0.63	-1.23	-0.64	-0.91
	2	-0.70	-1.32	-0.78	-1.11
	3	-0.73	-1.20	-0.69	-1.07
	4	-0.65	-1.02	-0.67	-1.13
	Std. dev.	0.04	0.1	0.06	0.1
PDM-3	1	-1.04	-4.76	-2.46	-4.31
	2	-1.00	-4.88	-2.18	-4.77
	3	-1.01	-4.81	-2.73	-4.73
	4	-1.08	-3.95	-2.69	-3.62
	Std. dev.	0.03	0.4	0.25	0.5
PDM-4	1	-6.06	-20.74	-8.33	-22.76
	2	-6.13	-20.88	-8.49	-23.51
	3	-6.38	-21.02	-8.07	-26.34
	4	-5.42	-21.71	-7.69	-23.12
	Std. dev.	0.4	0.4	0.35	1.6
PDM-5	1	-0.70	0.25	-0.83	-0.05
	2	-0.66	0.69	-0.64	0.0
	3	-0.67	1.66	-0.49	1.58
	4	-0.58	1.43	-0.66	2.06
	Std. dev.	0.05	0.14	0.65	1.0
PDM-6	1	-0.02	melted	-0.06	melted
	2	-0.14	melted	-0.14	melted
	3	-0.05	melted	-0.07	melted
	4		melted		melted
	Std. dev.	0.06		0.04	

Table F6
Length Changes after Heat Aging (%)

Sample		Exposure Period			
		7 days at 40°C	7 days at 100°C	28 days at 40°C	28 days at 100°C
PDM-1	1	-1.03	-1.70	-0.82	-1.46
	2	-1.29	-1.60	-0.74	-1.20
	3	-1.14	-1.08	-0.86	-1.14
	4	-0.55	-1.55	-0.92	-1.20
	Std. dev.	0.3	0.3	0.1	0.14
PDM-2	1	-0.65	-1.44	-0.91	-1.35
	2	-0.27	-1.45	-0.63	-1.57
	3	-0.30	-1.31	-1.02	-1.60
	4	-0.31	-1.30	-0.74	-1.58
	Std. dev.	0.18	0.08	0.17	0.12
PDM-3	1	-0.25	-1.88	-1.19	-1.24
	2	-0.54	-1.82	-0.24	-1.29
	3	-0.59	-2.18	-1.18	-1.53
	4	-0.23	-1.91	-1.49	-0.76
	Std. dev.	0.2	0.16	0.5	0.32
PDM-4	1	-2.83	-2.07	-3.37	-3.25
	2	-2.59	-1.93	-3.33	-3.32
	3	-2.88	-1.29	-3.37	-6.45
	4	-2.44	-1.83	-3.48	-3.04
	Std. dev.	0.2	0.34	0.06	1.63
PDM-5	1	-0.01	-0.44	-0.16	-0.77
	2	-0.42	-0.53	-0.36	-0.59
	3	-0.24	-0.38	-0.27	-0.81
	4	-0.10	-0.29	-0.04	-0.45
	Std. dev.	0.18	.014	0.1	.017
PDM-6	1	0.30	melted	0.10	melted
	2	0.23	melted	0.6	melted
	3	0.04	melted	0.49	melted
	4		melted		melted
	Std. dev.	0.13		0.26	

Table F7
Effect of Automotive Chemicals on Tensile Strength and Elongation

Sample	Tensile Strength (MPa)			Elongation (%)		
	Motor Oil	Ethylene Glycol	Water	Motor Oil	Ethylene Glycol	Water
PDM-1 1	20.16	17.36	17.95	243.6	438.6	397.5
2	excluded	excluded	excluded	excluded	excluded	excluded
3	19.71	excluded	17.69	262.9	excluded	368.3
4		20.11	19.09		452.0	347.5
Std. dev.	0.3	1.9	0.7	14	10	25
PDM-2 1	3.070	1.002	0.967	390.4	585.5	524.1
2	3.697	0.837	1.147	465.8	469.7	533.0
3	3.217	0.968	0.975	394.8	566.0	480.9
4	3.391	0.794	1.06	379.0	513.9	422.9
Std. dev.	0.3	0.1	0.01	39	52	50
PDM-3 1	3.166	3.128	3.246	757.3	698.3	776.1
2	3.673	3.057	2.773	863.0	676.4	663.5
3	3.290	2.982	3.565	783.6	705.4	815.9
4	excluded	3.077	3.118	excluded	742.9	759.8
Std. dev.	0.3	0.06	0.3	55	27	64
PDM-4 1	5.972	2.792	2.294	113.40	350.7	293.7
2	excluded	3.044	excluded	excluded	373.0	excluded
3	9.210	2.371	2.168	85.19	292.7	232.8
4	5.927	2.508	2.168	86.18	324.4	241.7
Std. dev.	1.9	0.3	0.07	16	35	33
PDM-5 1	6.800	5.001	5.027	719.9	686.2	655.9
2	7.729	6.085	7.019	721.4	749.6	791.8
3	7.853	5.309	7.222	790.3	696.6	767.0
Std. dev.	0.6	0.5	1.2	40	34	72
PDM-6 1	0.0499	0.2022	0.1907	803.7	1081	1008
2	0.0550	0.1986	0.2056	781.8	1121	1019
3	0.0512		0.1376	781.8		1048
4	0.0565		0.2364	820.2		1053
5			0.2509			1049
Std. dev.	0.003	0.002	0.02	19	28	20

Table F8a
Effect of Automotive Chemicals on Weight of Free Film Specimens - PDM-1 (%)

Medium	Sample	7 days immersion	14 days immersion	28 days immersion
Motor Oil	1	0.179	0.179	0.119
	2	0.158	0.053	0.00
	3	0.238	0.238	0.142
	Std. dev.	0.02	0.09	0.02
Ethylene Glycol	1	3.097	3.812	4.169
	2	2.561	3.074	3.432
	3	2.541	3.260	3.536
	Std. dev.	0.31	0.38	0.4
Water	1	2.809	3.476	4.333
	2	2.806	3.340	4.198
	3	3.125	3.891	4.658
	Std. dev.	0.18	0.28	0.24

Table F8b
Effect of Automotive Chemicals on Weight of Free Film Specimens - PDM-2 (%)

Medium	Sample	7 day immersion	14 day immersion	21 day immersion	28 day immersion
Motor Oil	1	2.54	3.06	3.32	3.41
	2	3.09	4.02	4.26	4.41
	3	2.49	3.27	3.81	3.66
	4	2.53	3.32	3.63	3.79
	Std. dev.	0.28	0.4	0.4	0.42
Ethylene Glycol	1	10.34	12.88	13.89	14.02
	2	10.99	13.22	13.64	14.21
	3	10.32	12.92	13.79	13.93
	4	10.36	12.56	13.11	13.59
	Std. dev.	0.32	0.27	0.35	0.26
Water	1	10.42	8.10	7.78	8.50
	2	8.21	9.13	9.21	9.35
	3	7.62	8.60	9.45	10.01
	4	8.68	9.01	9.35	9.77
	Std. dev.	1.20	0.46	0.78	0.66

Table F8c
Effect of Automotive Chemicals on Weight of Free Film Specimens - PDM-3 (%)

Medium	Sample	7 day immersion	14 day immersion	21 day immersion	28 day immersion
Motor Oil	1	-3.44	-3.92	-4.23	-4.61
	2	-3.60	-4.05	-4.68	-4.95
	3	-3.85	-4.39	-4.94	-5.13
	4	-4.34	-4.82	-5.23	-5.45
	Std. dev.	0.39	0.40	0.42	0.43
Ethylene Glycol	1	1.28	0.91	0.73	0.73
	2	1.28	0.96	0.48	0.64
	3	1.31	1.14	0.82	0.98
	4	1.10	1.02	0.86	0.78
	Std. dev.	0.15	0.10	0.17	0.14
Water	1	1.88	1.88	1.88	2.29
	2	1.84	1.71	1.84	2.10
	3	2.04	2.38	2.01	2.20
	4	1.80	1.80	1.92	2.05
	Std. dev.	0.10	0.30	0.07	0.11

Table F8d
Effect of Automotive Chemicals on Weight of Free Film Specimens - PDM-4 (%)

Medium	Sample	7 days immersion	14 days immersion	28 days immersion
Motor Oil	1	-12.80	-15.93	-18.33
	2	-12.94	-15.87	-18.10
	3	-14.42	-17.42	-18.80
	4	-12.59	-16.20	-18.45
	Std. dev.	0.83	0.72	0.29
Ethylene Glycol	1	-0.76	-2.34	-2.91
	2	-0.69	excluded	-1.31
	3	-0.86	-1.87	-2.23
	4	-0.50	-1.32	-2.26
	Std. dev.	0.15	0.51	0.66
Water	1	1.80	2.08	2.91
	2	1.95	2.23	3.15
	3	2.34	2.99	3.93
	4	2.11	2.49	3.32
	Std. dev.	0.23	0.4	0.43

Table F8e
Effect of Automotive Chemicals on Weight of Free Film Specimens - PDM-5 (%)

Medium	Sample	7 day immersion	14 day immersion	21 day immersion	28 day immersion
Motor Oil	1	1.89	2.57	3.09	3.55
	2	2.18	2.78	3.31	3.61
	3	1.98	2.76	3.20	3.66
	Std. dev.	0.15	0.11	0.11	0.06
Ethylene Glycol	1	6.19	5.02	4.76	4.76
	2	6.19	4.97	4.61	4.61
	3	5.49	4.99	4.65	4.48
	Std. dev.	0.40	0.02	0.08	0.14
Water	1	3.60	3.06	2.83	2.37
	2	3.14	2.60	2.51	2.06
	3	2.99	2.82	2.48	2.03
	Std. dev.	0.32	0.23	0.19	0.19

Table F8f
Effect of Automotive Chemicals on Weight of Free Film Specimens - PDM-6 (%)

Medium	Sample	7 day immersion	14 day immersion	21 day immersion	28 day immersion
Motor Oil	1	10.63	14.38	17.27	19.53
	2	8.39	12.22	14.96	17.44
	3	7.59	11.75	14.61	17.68
	Std. dev.	1.57	1.40	1.44	1.14
Ethylene Glycol	1	0.66	0.84	0.72	0.84
	2	0.59	0.75	0.91	0.95
	3	0.53	0.71	0.80	0.92
	Std. dev.	0.06	0.07	0.09	0.06
Water	1	0.51	0.77	0.95	1.13
	2	0.29	0.50	0.61	0.72
	3	0.53	0.81	1.03	1.03
	Std. dev.	0.13	0.17	0.22	0.21

Table F9a
Effect of Automotive Chemicals on Thickness of Free Film Specimens PDM-1 (%)

Medium	Sample	7days immersion	14 days immersion	28 days immersion
Motor Oil	1	-0.66	1.09	0.90
	2	-0.17	1.38	4.04
	3	-0.14	2.21	2.99
	Std. dev.	0.29	0.58	1.6
Ethylene Glycol	1	2.56	4.41	4.13
	2	-0.13	4.24	4.29
	3	-0.47	1.00	2.71
	Std. dev	1.6	1.92	0.9
Water	1	0.52	4.43	3.58
	2	1.12	2.98	3.13
	3	5.64	8.71	5.43
	Std. dev.	2.8	2.9	1.2

Table F9b
Effect of Automotive Chemicals on Thickness of Free Film Specimens PDM-2 (%)

Medium	Sample	7 days immersion	14 days immersion	21 days immersion	28 days immersion
Motor Oil	1	-0.62	-1.80	-0.88	-0.49
	2	0.58	-1.13	-1.93	-0.22
	3	0.48	-2.29	-1.69	-1.12
	4	-0.24	-1.03	-0.27	-0.56
	Std. dev.	0.57	0.59	0.76	0.38
Ethylene Glycol	1	-7.50	-3.15	-4.71	-2.31
	2	-10.24	-2.62	-7.69	-2.01
	3	-4.64	-1.44	-4.55	-2.94
	4	-4.98	-0.59	-0.16	-2.1
	Std. dev	2.6	1.15	3.1	0.42
Water	1	2.57	0.99	2.93	3.1
	2	3.47	5.16	4.92	5.98
	3	1.93	0.66	2.66	1.2
	4	-1.32	3.56	3.39	3.95
	Std. dev.	2.1	2.1	0.96	1.9

Table F9c
Effect of Automotive Chemicals on Thickness of Free Film Specimens PDM-3 (%)

Medium	Sample	7 days immersion	14 days immersion	21 days immersion	28 days immersion
Motor Oil	1	-5.27	-5.86	-5.57	-3.26
	2	-3.72	-6.78	-4.68	-5.16
	3	-2.77	-6.11	-3.71	-4.42
	4	excluded	-7.73	-2.98	-3.55
	Std. dev.	1.26	0.83	1.13	0.86
Ethylene Glycol	1	-0.45	-7.59	-1.65	-3.11
	2	0.52	-3.56	-0.67	-1.85
	3	-1.02	-6.77	-2.44	-3.86
	4	-0.19	-2.88	-2.73	-1.12
	Std. dev.	0.6		0.92	1.2
Water	1	0.40	excluded	0.74	1.41
	2	4.86	1.38	4.07	3.35
	3	excluded	0.09	3.13	excluded
	4	2.73	2.37	2.49	2.43
	Std. dev.	2.2	0.67	1.4	0.97

Table F9d
Effect of Automotive Chemicals on Thickness of Free Film Specimens PDM-4 (%)

Medium	Sample	7days immersion	14 days immersion	28 days immersion
Motor Oil	1	-2.05	-4.92	-6.02
	2	-3.14	-3.98	-6.25
	3	-5.66	-5.28	-6.98
	4	-3.10	-4.64	-5.94
	Std. dev.	1.5	0.55	0.47
Ethylene Glycol	1	-0.63	-1.59	-2.49
	2	0.03	-1.15	-2.40
	3	0.26	0.46	-1.18
	4	0.09	1.39	-0.18
	Std. dev.			
Water	1	1.53	2.67	2.43
	2	1.42	3.51	2.40
	3	2.36	2.24	2.94
	4	2.62	3.97	3.93
	Std. dev.	0.6	0.78	0.71

Table F9e
Effect of Automotive Chemicals on Thickness of Free Film Specimens PDM-5 (%)

Medium	Sample	7 days immersion	14 days immersion	21 days immersion	28 days immersion
Motor Oil	1	1.43	-1.32	2.26	3.01
	2	1.19	1.01	1.85	2.83
	3	-0.72	-0.30	0.76	4.26
	Std. dev.			0.77	0.8
Ethylene Glycol	1	4.47	2.08	1.73	3.08
	2	excluded	4.04	3.67	1.58
	3	3.71	4.92	2.82	2.10
	Std. dev.	0.4	1.4	0.9	0.7
Water	1	4.14	4.50	6.95	6.07
	2	1.99	3.03	4.11	3.86
	3	2.86	3.29	4.77	4.57
	Std. dev.	1.1	0.8	1.5	1.1

Table F10a
Tensile Strength of Free Film Specimens after Exposure to UV Radiation (MPa)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5	PDM-6
1	13.09	2.66	2.20	6.49	6.08	0.212
2	23.40	2.67	2.20	6.82	6.8	0.213
3	15.39	2.37	excluded	6.55	5.97	0.245
4	19.39	2.71	2.401	6.41	6.77	0.207
Std. dev.	4.5	0.16	0.1	0.2	0.4	0.02

Table F10b
Elongation of Free Film Specimens after Exposure to UV Radiation (%)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5	PDM-6
1	117.9	417.2	438.0	78.75	116.1	878.0
2	249.6	403.2	442.0	102.00	197.9	743.3
3	166.9	361.6	excluded	94.60	102.7	753.2
4	198.1	407.2	469.2	71.82	159.7	665.2
Std. dev.	55	24	17	14	43	88

Table F11a
Tensile Strength of Composite Specimens References (MPa)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5
1	5.09	2.79	1.33	1.14	2.15
2	4.49	2.68	1.23	1.26	excluded
3	excluded	2.48	1.46	1.35	2.22
4	4.47	2.56	1.57	1.04	2.29
5	6.22	2.66	1.46	0.91	excluded
Std. dev.	0.82	0.12	0.13	0.17	0.07

Table F11b
Elongation of Composite Specimens References (%)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5
1	233.5	203.8	16.86	217.7	790.8
2	148.7	178.5	18.84	199.8	excluded
3	excluded	161.5	21.82	216.7	609.8
4	127.9	189.4	22.31	184.9	639.6
5	210.2	183.4	23.80	205.8	excluded
Std. dev.	50	15	2.8	13	88

Table F12a
Tensile Strength of Composite Specimens Exposed to UV Radiation (MPa)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5
1	5.14	2.62	1.62	1.51	1.93
2	5.81	3.11	1.54	1.2	1.91
3	4.85	1.63	1.46	1.73	3.04
4	4.73	2.05	1.55	1.45	3.10
5	4.72	2.83	1.53		
Std. dev.	0.46	0.60	0.06	0.22	0.66

Table F12b
Elongation of Composite Specimens after Exposure to UV Radiation (%)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5
1	139.8	186.9	32.72	88.75	727
2	154.7	187.9	35.70	100.20	690
3	183.4	149.2	24.29	172.0	excluded
4	127.9	116.0	22.31	164.1	836
5	166.6	204.8	32.23	-	776
Std. dev.	22	36	6	43	63

Table F13
Water Vapour Transmission of Free Film Specimens (g/h·m²)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5	PDM-6
1	0.2798	0.3391	0.6625	0.1663	3.2652	7.92x10 ⁻⁴
2	0.2719	0.3233	0.5966	0.1861	2.9577	5.28x10 ⁻⁴
3	0.3115	0.3220	0.5913	0.1966	2.8930	5.28x10 ⁻⁴
Std. dev.	0.021	0.009	0.039	0.015	0.199	1.52x10 ⁻⁴

Table F14
Abrasion Resistance of Free Film Specimens

Sample		CS-17 Wheels		H-10 Wheels	
		Wear Index	Depth Abraded	Wear Index	Depth Abraded
PDM-1	1	0.0397	0.109	0.0565	0.097
	2	0.0350	0.0889	-	-
PDM-2	1	0.0060	0.0737	0.014	0.060
	2	0.0147	0.0406	-	-
PDM-3	1	0.881	0.4267	1.2165	0.490
	2	0.875	0.2108	-	-
PDM-4	1	0.2563	0.2921	0.317	0.305
	2	0.3070	0.2819	-	-
PDM-5	1	-0.0042	n. a.	0.042	0.092
	2	-0.0025	n. a.	-	-

negative values indicate an increase in sample weight

Table F15
Cold Temperatures Properties of Free Film specimens

Sample		Tensile Strength (MPa)			Elongation (%)		
		0°C	-20°C	-40°C	0°C	-20°C	-40°C
PDM-1	1	20.84	22.75	43.22	71.25	8.09	3.51
	2	19.40	24.50	51.91	55.23	7.02	3.81
	3	18.74	25.29	39.34	57.21	11.9	2.75
	4	17.74	26.55	-	42.21	10.99	-
Std. dev.		1.3	1.6	6.4	12	2.3	0.55
PDM-2	1	20.09	30.80	53.03	239.2	157.1	7.17
	2	20.79	35.79	53.28	250.8	174.1	5.34
	3	20.57	excluded	52.98	238.2	excluded	4.27
	4	-	35.92	53.52	-	160.8	3.97
Std. dev.		0.4	2.9	0.2	7	9	1.4
PDM-3	1	2.87	8.37	13.36	567.3	502.7	219.2
	2	2.87	9.02	16.23	605.6	567.9	292.5
	3	excluded	7.64	16.98	excluded	445.7	234.4
	4	2.94	8.57	17.98	619.9	565.6	304.8
Std. dev.		0.04	0.6	2	27	58	42
PDM-4	1	excluded	excluded	23.13	excluded	excluded	3.97
	2	7.19	7.67	17.43	75.98	21.21	2.14
	3	7.29	7.27	22.12	77.96	25.63	2.29
	4	6.93	7.46	14.52	83.15	18.92	1.68
Std. dev.		0.2	0.2	4	3.7	3.4	1.0
PDM-5	1	excluded	24.58	17.13	excluded	3.81	1.93
	2	9.93	14.90	17.20	297.4	3.81	3.20
	3	9.15	18.02	19.27	249.3	4.58	3.21
	4	9.85	-	13.92	273.0	-	2.44
Std. dev.		0.4	5	2.2	24	0.4	0.6
PDM-6	1	0.067	0.1958	0.609	556.1	21.21	7.02
	2	excluded	0.1795	0.456	excluded	187.4	3.66
	3	0.99	0.1712	0.363	183.2	17.39	3.66
	4	-	0.1994	-	-	29.60	-
Std. dev.		0.02	0.01	0.12	264	82	3

Table F16
Recovery from Elongation of Free Film Specimens (%)

Sample	PDM-1	PDM-2	PDM-3	PDM-4	PDM-5	PDM-6
1	86.80	97.85	95.20	59.85	71.75	88.25
2	86.45	99.70	92.35	61.85	70.00	88.33
3	87.90	97.80	95.60	52.26	68.90	86.92
4	87.05	98.80	91.85	broke	67.05	
Std. dev.	0.6	0.9	1.9	5.1	1.9	0.8

Table F17
Permeance of Composite Membrane Specimens (ng/s·m²·Pa)

Sample		w/c 0.45	w/c 0.45 air entrained	w/c 0.55	w/c 0.55 air entrained
Control	1	21.4	32.9	32.5	45.1
	2	20.4	32.1	33.6	48.3
PDM-1	1	4.19	6.35	8.07	8.16
	2	5.02	5.85	5.62	6.21
PDM-2	1	2.36	3.19	4.31	1.57
	2	5.97	1.90	3.52	2.74
PDM-3	1	4.74	5.64	5.26	5.28
	2	4.64	5.38	4.52	5.33
PDM-4	1	1.38	0.88	1.38	1.07
	2	1.24	1.05	5.71	1.12
PDM-5	1	4.55	3.47	5.59	3.86
	2	3.81	4.76	3.69	4.05
PDM-6	1	n. a.	n. a.	n. a.	n. a.
	2	n. a.	n. a.	n. a.	n. a.

Table F18
Tensile Ahesive Strength of Membrane to Concrete (MPa)

Sample		w/c 0.45	w/c 0.45 air entrained	w/c 0.55	w/c 0.55 air entrained
PDM-1	1	4.88	4.17	3.88	4.88
	2	4.88	4.35	3.04	4.88
PDM-2	1	2.39	1.45	2.39	1.83
	2	2.34	epoxy failure	2.11	1.78
PDM-3	1	1.78	1.54	1.36	1.59
	2	1.92	1.64	1.36	1.54
PDM-4	1	4.21	3.32	3.37	3.14
	2	3.42	3.28	3.46	3.18
PDM-5	1	3.74	3.56	2.62	2.81
	2	epoxy failure	epoxy failure	2.48	2.95

Table F19
Length Change after 100 Freeze/Thaw Cycles (%)

Sample		w/c 0.45	w/c 0.45 air entrained	w/c 0.55	w/c 0.55 air entrained
PDM-1	1	0.974	0.004	1.235	0.047
	2	1.672	0.005	0.86	0.034
PDM-2	1	0.006	0.004	0.007	0.006
	2	0.006	0.003	0.006	0.005
PDM-3	1	-0.063	-0.051	-0.008	-0.012
	2	-0.013	0.004	-0.027	-0.015
PDM-4	1	*	1.564	0.014	0.009
	2	0.628	1.179	0.006	0.029
PDM-5	1	0.008	-0.016	-0.018	-0.011
	2	0.026	-0.012	-0.043	-0.025
PDM-6	1	*	12.73	*	12.71
	2	*	12.70	*	12.71
Control	1	*	11.32	*	12.85
	2		12.57		12.95

* samples completely deteriorated

Table F20
Thickness of Free Film Membranes

Membrane	Thickness (mm)	Standard deviation	Membrane	Thickness (mm)	Standard deviation
PDM-1	0.903	0.118	PDM-4	1.008	0.147
PDM-2	1.074	0.096	PDM-5	0.770	0.201
PDM-3	0.689	0.195	PDM-6	2.361	0.579